APPENDIX W. SOPN RIVERINE AND LACUSTRINE CONCEPTUAL MODEL

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Acknowledgements

Documentation has been adopted extensively from materials prepared for the Northern and Southern Colorado Plateau I&M Networks (Scott et al. 2005) [Sections 1, 2, 4, and 5] and the Great Lakes I&M Network (Inland Lakes, Sager 2004) [Section 3].

W.1. INTRODUCTION AND BACKGROUND

W.1.1. Purpose and Content of This Appendix

This appendix presents conceptual models describing the structure and functioning of aquatic and riparian ecosystems[1] of the Southern Plains I & M Network (SOPN). These models have been developed to support the selection of vital signs for use in long-term monitoring of SOPN aquatic and riparian resources in 11 National Park Service units located in Texas, New Mexico, Colorado, Kansas, and Oklahoma (see Appendix E for natural resource summaries of each park).

Conceptual models for stream, reservoir, and riparian ecosystems of SOPN parks are presented in Sections 2, 3, and 4, respectively. Each section begins with a general description of ecosystem drivers, stressors (both anthropogenic and natural), major ecosystem components/attributes, and a summary of indicators of ecosystem function and condition. A second subsection describes natural/desired ecosystem function, including a detailed description of ecosystem attributes and processes and functional relationships between abiotic and biotic components. A third subsection describes specific ecosystem stresses, responses, and indicators of ecosystem condition as an aid in selecting vital signs representing the greatest number of key ecosystem processes and attributes. Section 2 also includes a discussion of the benefits of stream classification for long-term monitoring of stream and riparian ecosystems. This appendix closes with a discussion of the value of aquatic macroinvertebrates as indicators of aquatic ecosystem function and condition.

Included in this report are all aquatic and riparian ecosystems of SOPN parks - lotic (flowing water systems), including perennial and intermittent streams/rivers, and lentic (standing water systems), comprised primarily of reservoirs. In general, the abiotic characteristics of lotic systems are more heterogeneous, increasing the biological diversity of stream ecosystems (Thorp and Covich 1991). An additional model for palustrine freshwater marshes is presented as a separate model elsewhere in Appendix V.

W.1.2. Water Resources of the Southern Great Plains

The SOPN has recognized from the beginning that the water resources of the network, whether in the form of precipitation or in water bodies, are a primary component of all the network ecosystems. Water has long been a scarce resource in the western and central portions of the Great Plains. Surface water is important for ecological reasons, but the presence of surface water was also important for European settlers. Eight of the 11 SOPN parks were created, at least in part, due to their cultural significance to Native Americans or early settlers. All of these cultural parks are located near flowing rivers because of their importance to Native Americans and early settlers. So while, surface water is still a rarity in the Great Plains, SOPN parks have a higher proportion of surface waters then would occur on a random selection of prairie areas. Lake Meredith NRA and Chickasaw NRA were created largely for the large reservoirs present. All SOPN parks except for Capulin Volcano NM, Alibates Flint Quarries NM, and Fort Union NM have permanent water resources, with the latter two being located very close to permanent water.

Many of the basic features of historical Great Plains streams, such as flow and substrate, are unknown (Matthews 1988), as these were among the first things altered by early settlers. Great

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[1]An ***ecosystem*** is a spatially explicit unit of the Earth that includes all of the organisms, along with all components of the abiotic environment within its boundaries (Likens 1992, cited by Christensen et al. 1996:670). *Ecosystem structure* refers to the types, amounts, and spatial arrangement of biotic and abiotic components of an ecosystem. *Ecosystem functioning* refers to the flow of energy and materials through the arrangement of biotic and abiotic components of an ecosystem (includes processes such as primary production, trophic transfer from plants to animals, nutrient cycling, water dynamics and heat transfer).

Plains Rivers generally flow from west to east and are characterized by extreme turbidity, high evaporation rates, moderate flow velocity and dynamic channels. Great Plains streams fall into three categories: the shallow stream with shifting sand beds; clear brooks, ponds, and marshes supported by seeps and springs; and residual pools of intermittent streams (Cross and Moss 1987). In general, streams in the southern plains are characterized by irregular flow, small particle size in substrates, and a distinct wet-dry cycle. Much of the water originates from the western mountains, while many types of sediment originate from thunderstorm runoff on the Great Plains. Early travelers were inhibited by quicksands in small channels, fine particles held in suspension. These fine particles also cause extreme turbidity during low flows. Like the plains themselves, river temperatures can fluctuate widely with summer, open-river water temperatures exceeding 86°F (30°C), and high salinity levels due to salt- and gypsum-laden groundwater.

The High Plains aquifer, also known as the Ogallala aquifer, is located in the central Great Plains and consists predominantly of unconsolidated gravel, sand, silt, and clay (the Ogallala Formation). The aquifer is essential for agriculture, water supply (urban and residential), and environmental resources in the area, underlying about 20% of irrigated farmland in the High Plains and providing about 30% of water for irrigation (Huntzinger 1996). Precipitation is the principal source of recharge to the aquifer, but additional recharge occurs as seepage from streams and lakes. Discharge from the aquifer occurs as evapotranspiration where the water table is near the surface.

There have been significant changes in the amount and permanency of surface and ground water since pre-Columbian times as a result of ranching (e.g., stock ponds), irrigation, flood control, and other anthropogenic changes. Few major rivers in the Great Plains still exhibit the conditions evident before agricultural development and water management had occurred. Dams, irrigation, municipal withdrawals, and other land use changes have significantly impacted flows and water levels in streams, rivers, reservoirs, and wetlands of the Great Plains (Cross and Moss 1987, Longo and Yoskowitz 2002). Sediment deposition is part of reservoir design but remains a maintenance concern. In virtually all the river systems, dewatering has altered the timing and extent of flows, downstream temperatures, levels of dissolved nutrients, sediment transport and deposition, and the structure of plant and animal communities. Dams exist at three SOPN parks and all of the SOPN aquatic resources are affected by altered flows primarily from agriculture and development.

Water quality and quantity are high priority issues at SOPN parks. Water quality throughout the Great Plains has also been affected by herbicides and other pollutants, and SOPN parks are no exception. Agricultural use of nitrogen fertilizers is the largest source of nitrates in near-surface aquifers in the midcontinent (Koplin et al. 1994). For example, over 100,000 metric tons of pesticides (herbicides, insecticides, and fungicides) were applied in the midcontinent in 1991, often to control nonindigenous plants and animals. Effects of these pollutants on the quality of human life and on the integrity of the ecological community are largely unknown. The U.S. Environmental Protection Agency has initiated an effort to develop stressor information to help recognize areas where urban development, agricultural nonpoint pollution (pesticides, toxic chemicals, nutrient pollution), and agricultural development may exacerbate ecological decline. Elevated *E.coli* levels are also a concern at Chickasaw NRA.

Groundwater depletion is of regional concern for both Great Plains ecology and human needs. Kromm and White (1992) observed that groundwater depletion has destroyed much of the water-supported habitat for fish and mammals in parts of the Great Plains. They reported that more than 700 miles (1,127 km) of once permanently flowing rivers in Kansas no longer flow year round. From the mid-1940's to 1980, groundwater levels dropped 10 to 50 feet in most areas of the High Plains aquifer, and 50 to more than 100 feet in heavily irrigated portions of the Southern High Plains of Texas, out of a total saturated thickness of 650 feet or less (U.S. Geological Survey Groundwater Atlas of the United States; Dugan et al. 1994). Groundwater quantity and quality are important resource and management issues at Chickasaw NRA and Bent's Old Fort NHS, in particular, where large-scale groundwater developments have been proposed and (in the case of Bent's Old Fort) irrigation pumping is significant.

W.1.2.1. Streams and Rivers (Riverine Systems)

The study of prairie streams and rivers is still in the ecological exploration stage compared to forested streams. The standard River Continuum Concept (Vannote et al. 1980) may not apply to prairie streams. The most detailed work on prairie streams has been completed at King's Creek located at the Konza LTER site in tall-grass prairie (Gray and Dodds 1998, Gray et al. 1998), with less work occurring in the mixed- and short-grass prairies.

Most watersheds in the SOPN drain the eastern slope of the Rocky Mountains and flow from west to east, traversing plains of Quaternary sediments underlain by the Ogallala aquifer (Eschner et al. 1983). Prairie streams and rivers are usually characterized by stable flows during spring and early summer, and intermittent flow to completely dry in the summer. Floods can scour the channel at any time. Flow in the main stem of rivers during early summer is derived from snowmelt runoff, which can decline and leave some channels intermittent during the summer (Jordan 1891, Mead 1896, Eschner et al 1983, Cross et al. 1985). In the plains tributaries, the flows come primarily from spring rains and summer thunderstorms which produce flash floods due to impermeable soils that produce high runoff (Fausch and Bramblett 1991).

Historically rivers would have resulted in narrow gallery forests. However these riparian forests have expanded since pre-European times (Wedel 1986, Knopf and Scott 1990). Fringe riparian forests would have cycled on 50-150 year intervals (Scott et al. 1996) due to large runoff periodically eliminating woody species and contributing large woody debris to channels. Some streams in the west may have been almost devoid of trees. As the stream flow varies, so does physicochemical variables such as water temperature, dissolved oxygen, turbidity, and salinity (Matthews and Zimmermann 1990). Channel beds of large rivers were historically shifting sand, wide and shallow with braided shifting sand beds that formed numerous bars and islands, and turbid water due to the high sediment load (Cross and Moss 1987, Bramblett and Fausch 1991a). The biotic community that has evolved with prairie streams has developed the ability to adjust to a patchy environment that is created by the variable streamflow and associated large changes in temperature and turbidity.

Variable stream flows and regular droughts create a particularly harsh environment for fish. Little is known about the original distributions and ecology of many fish in the Great Plains because habitats were drastically altered before observations had been made (Eschner et al. 1983). Great Plains fish species can be characterized by being relatively small (<8 inches (200 mm)), highly vagile, having life spans <6 years, and being well-adapted to withstand floods and extremes during droughts (Fausch and Bestgen 1997). Most plains fish species are generalists that occupy habitats and consume food resources in proportion to what is available (Bramblett and Fausch 1991b).

With the discovery of gold in the mountains west of Denver in 1858, development progressed rapidly. Water development began with small ditches that were followed by larger canals for irrigating terraces in the 1840's to 1860's. Since some of the rivers went dry, reservoirs were built in the late 1800's and early 1900's. With the demand for water still increasing, groundwater began being pumped from the Ogallala aquifer in the 1930's (Fausch and Bestgen 1997). These water development projects had drastic effects on river channels, including narrowing, and becoming more sinuous due to encroaching vegetation (Nadler and Schumm 1981). Reduced runoff allowed seedlings of woody vegetation to stabilize shifting sand bars. The vegetated sand bars trapped sediment and eventually attached to the floodplain, changing the straight wide braided channels to single narrow sinuous ones. The increase in cottonwood (*Populus deltoides*) riparian forests now contributes more woody debris to the stream channel then historic levels.

The creation of the John Martin Reservoir on the Arkansas River in 1942 combined with groundwater pumping in Colorado and western Kansas completely eliminated flow in 100 miles (160 km) of the Arkansas, except for discharge from municipal wastewater treatment plants (Fausch and Bestgen 1997).

W.1.2.2. Reservoirs (Lacustrine Systems)

Reservoir systems are the principal resources at two parks in the SOPN, LAMR and CHIC, and therefore drive many of those Park's management decisions and visitor usage. Additionally, the Pedernales River is impounded by three dams in, and adjacent to at LYJO. These artificial lakes were originally designed to satisfy the increasing need for water resources. They supplied water to surrounding municipalities, industries, agricultural communities, and regulated stream flow. Today, reservoirs continue to satisfy the well-defined economic objectives for which they were developed. However, at the same time reservoir systems are posing challenges to natural resource managers, including those at CHIC, LAMR, and LYJO. When reservoirs replace riverine ecosystems, new physical and biological conditions are created that managers must protect and preserve. Reservoirs have unique operational and maintenance characteristics compared to those of natural lakes (Flug 1998).

The effects that reservoirs have upon the surrounding natural ecosystems are broad. For example, man-made reservoirs, unlike natural lakes, tend to experience large fluctuations in water levels, and are highly susceptible to bank instability and erosion (Flug 1998). Furthermore, reservoirs trap river sediments, often create deltas at the mouth of river inflows, alter water quality and temperature, create habitat for non-native fish species, present an obstacle to native fish migration, and may create wetlands or new riparian resources (Flug 1998). For recreational users, reservoirs provide lake resources that include swimming, boat access, beaches, and sport fishing; however, the reservoir may have displaced historical viewsheds.

The effects of large dams on natural rivers are well documented (Vanoni 1975). Typically, rivers downstream from large dams experience fewer and smaller floods. Water released below dams may cause erosion that degrades stream beds, eroding bars and cutting into vegetated stream banks. Upstream of dams, sedimentation increases. In general, dams induce changes in sediment transport which lead to changes in river substrates (bed composition), channel dimensions, channel bars, and channel stability (Flug 1998), as well as turbidity and other water quality characteristics (e.g., temperature). Downstream of dams, decreases in turbidity alter light penetration – thus, primary production and fish and macroinvertebrate habitat.

Regulated flow releases from dams can provide benefits for boating and swimming, extreme fluctuations can be detrimental to recreational water use. These fluctuations also favor non-native vegetation species that may proliferate and out-compete native species that have evolved and adapted to natural flow cycles and stream dynamics (Flug 1998).

W.1.2.3. Prairie Wetlands (Palustrine Systems)

Emergent wetlands naturally form in places where groundwater discharges or surface water collects for some time in a manner sufficient to saturate soils. Such places in the Great Plains include depressions surrounded by upland and sloped areas below sites of groundwater discharge. Small prairie wetlands play an important role in Great Plains hydrology by storing surface water, moderating floods, improving water quality, and by recharging ground water and soil moisture. These wetlands are also highly productive habitat for waterfowl and other wildlife in a generally arid region. The disruption of natural processes such as fire and grazing since pre-European times has led to domination of these wetlands by robust, emergent plants. Climate, fire, and grazing previously controlled the diversity and abundance of vegetation in prairie wetlands. As these processes have changed, belowground seed reserves favor those species with seeds that germinate under a wide range of conditions, such as cattail, purple loosestrife, and other nonindigenous species. Cattail, once rare on the Great Plains, has spread across thousands of prairie wetlands.

Persistent emergent wetlands (freshwater marshes) (Cowardin et al. 1979) are the major type of palustrine wetland within SOPN and they are present at BEOL, SAND, CHIC, PECO, and LAMR. These wetlands dominated by persistent vegetation present for most of the growing season in most years. The vegetation generally remains standing from one year to the next. Wetlands without persistent vegetation are also included in this system if they are< 20 acres (8 ha), < 6.7 feet (2 m) deep during low water times, and no portion of the boundary contains wave-formed or bedrock shoreline. Freshwater marshes are characterized by: 1) emergent, soft-stemmed aquatic plants such as cattails, arrowheads, reeds, and other species of grasses and sedges; 2) a shallow water regime; and 3) generally shallow deposits of peat. These wetlands are usually dominated by perennial plants.

In the Great Plains wetlands comprise a small portion of the landscape, but they are often the areas of highest species diversity. Despite comprising <10% of the landscape in North America (on an areal basis), wetlands are important habitat for 68% of birds, 66% of mussels, and 75% of amphibians on the U.S. list of threatened and endangered species (Mitsch and Gosselink 2000). Wetland losses have been extensive in the SOPN Region. Dahl (2000) estimated that between 51 and 75% of wetlands had been lost in Texas and Oklahoma and between 25 and 50% in Kansas, Colorado, and New Mexico. Agriculture and urbanization are the dominant human influences on Great Plains wetlands.

Agricultural activities outside park boundaries pose threats to wetlands with SOPN parks. Runoff contaminated with sediment, nutrients, and pesticides reach park wetlands through waterways and drainages that have inadequate buffer zones. Aerial deposition of pesticides and nutrients has been documented in wetlands downwind of agricultural areas. Wetland destruction and fragmentation on adjacent lands threatens wetland species dependent on migration or dispersal corridors. The primary stressors associated with agricultural activity are drainage, sediments, nutrients, and toxicants.

W. 1.3. Overview of Stream, Reservoir, and Riparian Ecosystem Models

For the purposes of this work, stream deep water habitats and riverine wetlands are described by the stream ecosystem model. Palustrine wetlands and upland riparian zones associated with streams are described in the riparian model, consistent with U. S. Fish and Wildlife guidelines for the classification of wetlands and deep water habitats of the United States (Cowardin et al. 1979). Reservoir deep water habitats and lacustrine wetlands at Lake Meredith and Chickasaw National Recreation Areas, as well as spring pool habitat at Chickasaw, are described by the reservoir ecosystem model. Again, palustrine wetlands and upland riparian zones associated with SOPN reservoirs (and spring pools) are described in the riparian model. The physical boundaries and distinguishing characteristics of stream, reservoir, and riparian models are shown in Figure 1. Palustrine wetlands, are described in Appendix V, represent a subset of riparian ecosystems (Mitsch and Gosselink 2000) as shown in Figure 2.

An important goal of conceptual model development is to depict how natural drivers (e.g., climate) and anthropogenic stressors affect ecosystem structure and functioning. SOPN aquatic and riparian models are presented as a combination of diagrams and tables showing associations between significant ecosystem features (attributes and processes) and the impacts of existing and potential ecosystem stresses in sufficient detail to support the development of the SOPN monitoring program. No single conceptual model can satisfy all needs. Spatially explicit applications, such as ecological resource assessments, monitoring design, and landscape-level ecological modeling will ultimately require site-specific models. The goal of the present modeling effort is to provide generalized ecological models to facilitate communication among scientists,

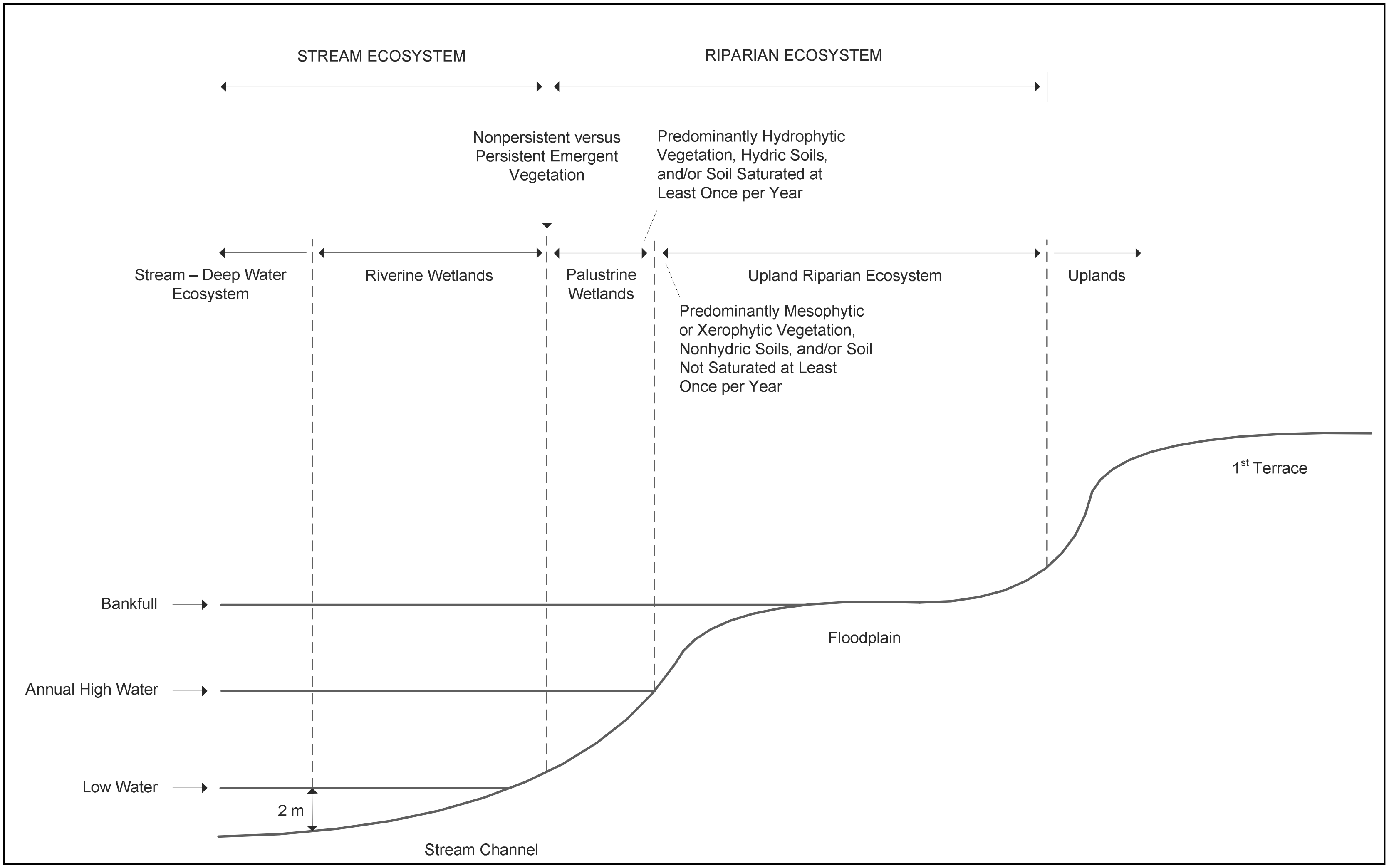


Figure 1. Physical boundaries of stream, reservoir, and riparian ecosystem models (Cowardin et al. 1979).

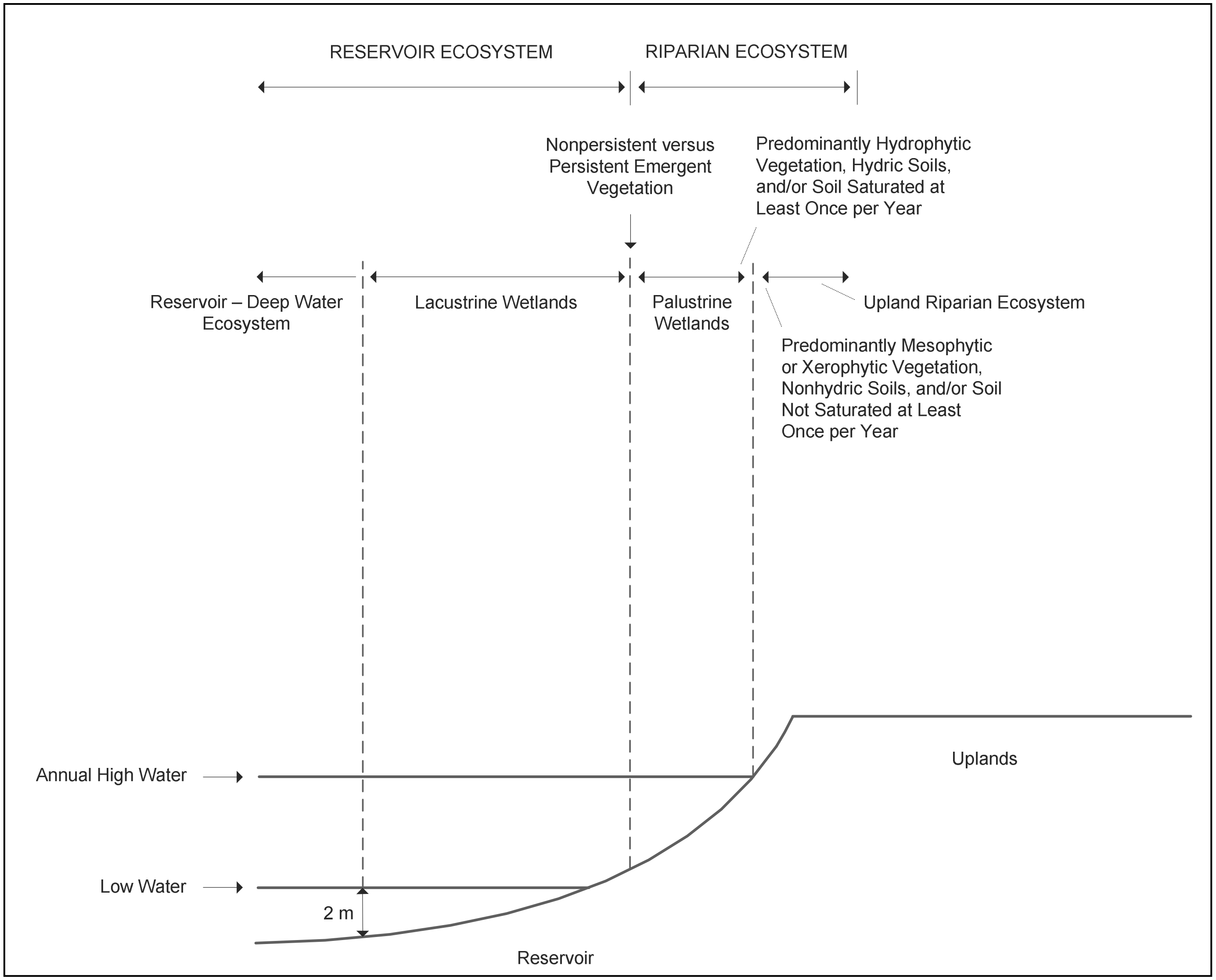


Figure 1 – *Continued*

managers, and the public regarding ecosystems and how they are affected by human activities and natural processes. Consequently, the models presented are generalized to circumscribe the diversity of aquatic and riparian ecosystems found in SOPN park units.

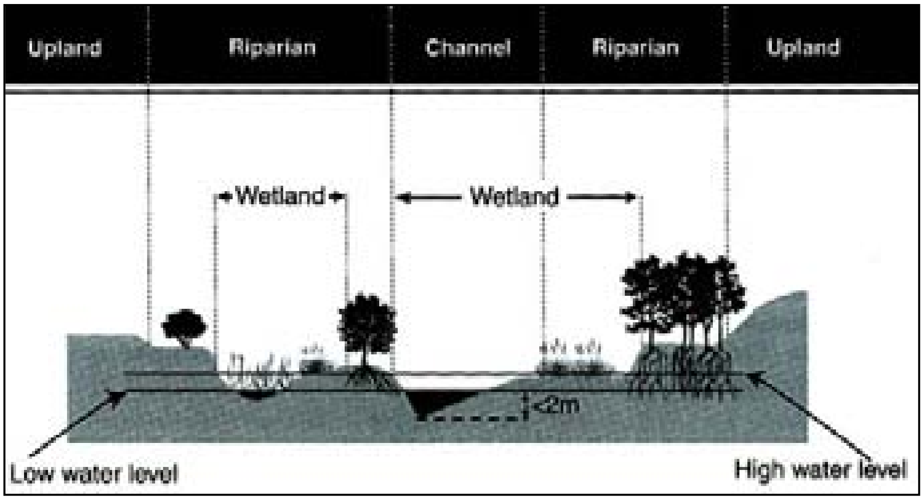


Figure 2. Palustrine wetlands as a subset of riparian ecosystems. From Mitsch and Gosselink (2000).

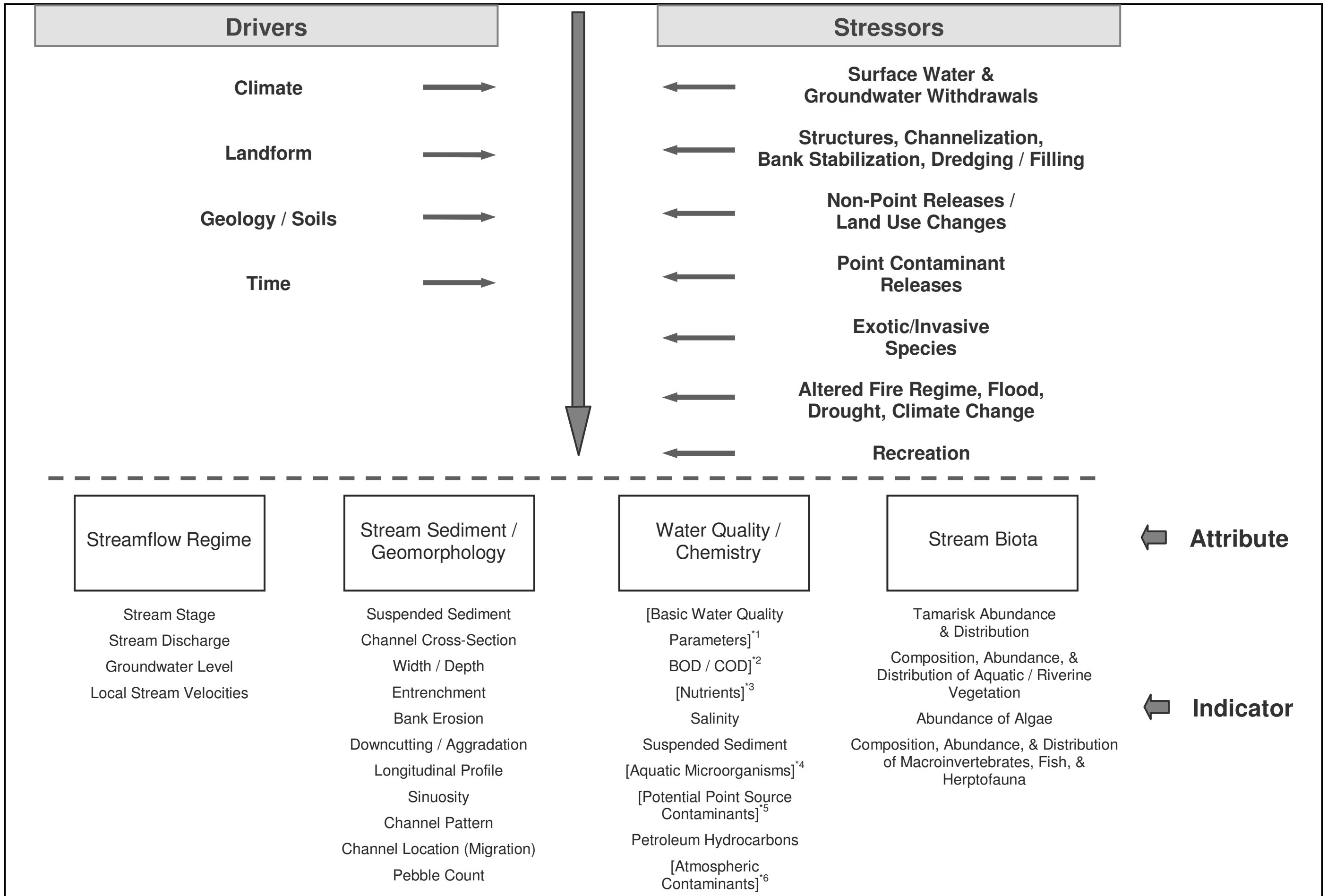
W. 2. STREAM ECOSYSTEM MODEL

The SOPN has adopted a modified version of the Jenny-Chapin model as a general ecosystem framework for guiding the development of conceptual models and consideration of vital signs (see Chapter 2, Figure 9 for Jenny-Chapin Model). Jenny (1941, 1980) proposed that soil and ecosystem processes are determined by five *state factors* – climate, organisms, relief (topography), parent material, and time since disturbance. Jenny's state-factor approach has been widely applied as a framework for examining temporal and spatial variations in ecosystem structure and functioning (e.g., Walker and Chapin 1987, Vitousek 1994, Seastedt 2001). Chapin et al. (1996) recently extended this framework to develop a set of ecological principles concerning ecosystem sustainability. They defined "...a sustainable ecosystem as one that, over the normal cycle of disturbance events, maintains its characteristic diversity of major functional groups, productivity, and rates of biogeochemical cycling" (Chapin et al. 1996:1016). These ecosystem characteristics are determined by a set of four "interactive controls" – climate, soil-resource supply, major functional groups[2] of organisms, and disturbance regime – and these interactive controls both govern and respond to ecosystem attributes. Interactive controls are constrained by the five state factors, which determine the "constraints of place" (Dale et al. 2000).

W.2.1. Summary of Drivers, Stressors, Attributes, and Indicators of Stream Ecosystem Function and Condition

Regional climate, atmospheric conditions, geology, landform, time, and upland watershed characteristics are drivers (major forces of change) for stream ecosystems of SOPN parks (Figure 3).

[2] ***Functional groups*** are groups of species that have similar effects on ecosystem processes (Chapin et al. 1996). This concept is generally synonymous with ***functional types***.



*1 Water temperature, pH, dissolved oxygen, major cations and anions, conductivity, alkalinity, and turbidity.
*2 Biological oxygen demand, chemical oxygen demand.
*3 Nitrogen and phosphorous.
*4 Bacteria, viruses, and protozoa.
*5 Synthetic organic compounds, petroleum hydrocarbons, heavy metals, pesticides, and other toxic substances, as applicable.
*6 Nitrogen and sulphur compounds, mercury and other metals, pesticides, as applicable.

Figure 3. Overview of drivers, stressors, attributes, and indicators of stream ecosystem function and condition.

W.2.1.1. Hierarchy of System Drivers

Time, Landform, Geology, and Climate - Over geologic time scales, Schumm and Lichty (1965) describe four independent variables that influence the erosional evolution of a landscape and its hydrology; (1) time, (2) initial topographic relief, (3) geology, and (4) climate (Table 1). The initial relief of a landscape represents potential energy. Over time, this energy is transformed to kinetic energy as climate, acting on the underlying geological materials, progressively modifies landscape morphology through the process of erosion. Eight additional dependent variables, elements of fluvial systems, influence the nature of aquatic ecosystems through their effects on streamflow and sediment transport. These variables, discussed in more detail in subsection *'Upland Watershed Characteristics'*, include: (5) vegetation, (6) watershed relief, (7) watershed hydrology, (8) drainage network morphology, (9) hillslope morphology, (10) runoff and sediment flux, (11) valley morphology and channel/floodplain form, and (12) depositional processes and patterns (Schumm 1981).

Precipitation regime is the most important climatic factor shaping the characteristics of aquatic ecosystems in SOPN parks. Precipitation inputs are key drivers of fluvial geomorphic processes and support water-limited ecological processes, including primary production, nutrient cycling, and plant reproduction (Noy-Meir 1973, Comstock and Ehleringer 1992, Whitford 2002). Precipitation seasonality (i.e., timing in relation to the annual cycle of potential evapotranspiration) is of particular importance because it strongly controls the partitioning of precipitation into various compartments of the hydrologic budget – evaporation, transpiration, runoff, soil-water storage, and streamflow. Because of its effects on hydrologic partitioning, precipitation seasonality is a major determinant of aquatic ecosystem dominance by different plant life forms and functional groups (Bagstad et al. in press).

Table 1. Fluvial system variables over geologic time scales. From Scott et al. (2005), after Schumm (1981)

Fluvial System Variables	Dependence of Variables
1. Time	Independent
2. Initial Relief	Independent
3. Geology (rock type and geologic structure)	Independent
4. Climate	Independent
5. Vegetation (type and cover)	Dependent on climate and geology (soils)
6. Relief (percentage of watershed remaining above	Dependent on preceding variables
7. Runoff and sediment yield (from upland watershed)	Dependent on preceding variables
8. Drainage network morphology (stream density, channel shape, gradient and slope)	Dependent on preceding variables
9. Hillslope morphology (hillslope angle and length)	Dependent on preceding variables
10. Discharge of water and sediment (from the watershed to the valleys)	Dependent on preceding variables
12. Depositional system (alluvial fan, delta)	Dependent on preceding variables

Precipitation regime also plays a major role in shaping the aquatic macroinvertebrate community. For example, a study in the United Kingdom demonstrated that the North Atlantic Oscillation (NAO) has significant effects on the growth and phenology of aquatic macroinvertebrates (Briers et al. 2004). Predicted time for mayfly nymph development varied by nearly two months due to alterations in winter stream thermal regime which resulted from fluctuations in the NAO. Variations in growth and the phenology of benthic invertebrates due to the NAO, in turn, influences temporal fluctuations in the composition and dynamics of stream communities (in the United Kingdom). Variations of this type can result in mismatches between the timing of life history stages, leading to changes in the biotic or physical environment that may have important long-term consequences for stream ecosystem function (Briers et al. 2004). Monitoring strategies can also be affected as changes in phenology lead to shifts in benthic community composition by altering normal seasonal changes in relation to a fixed survey date (Briers et al. 2004).

Regional precipitation patterns are affected by global-scale fluctuations in sea-surface temperatures, atmospheric pressure, and atmospheric circulation patterns that vary at two different time scales (Hereford et al. 2002). Short-term, inter-annual variations in precipitation are related in part to the occurrence of El Niño and La Niña conditions – the two contrasting phases of the El Niño – Southern Oscillation (ENSO) phenomenon that is driven by variations in sea-surface temperatures in the eastern tropical Pacific Ocean (Hereford and Webb 1992, Cayan et al. 1999, Hereford et al. 2002). Hereford et al. (2002) found that the detailed relationships were complex, but that strong El Niño episodes generally increased the variability of warm-season precipitation or the frequency of above-normal cool-season precipitation. In contrast, strong La Niña episodes tended to cause normal, low-variability warm-season precipitation and below-normal cool-season precipitation. Whether characterized by dry or wet conditions, extreme years featuring floods or droughts can have long-lasting consequences for ecosystem structure and functioning by causing episodes of plant mortality or establishment (Burkham 1972, Ehleringer et al. 2000, Friedman and Lee 2002).

Decadal-scale variations in precipitation patterns are related to a recently recognized phenomenon known as the Pacific Decadal Oscillation, or PDO (Mantua and Hare 2002, Hereford et al. 2002). Precipitation variability associated with the PDO is partly related to cyclical variations in sea-surface temperatures in the northern Pacific Ocean, although mechanisms driving PDO variability remain poorly understood (Mantua and Hare 2002).

In addition to temporal variability, spatial variability is a defining attribute of precipitation regimes in dry regions (Noy-Meir 1973, Whitford 2002). Topography and storm type are two factors that control spatial variability in precipitation. On a local scale, precipitation tends to increase with increasing elevation due to orographic effects of topography (precipitation caused by adiabatic cooling of rising air masses), but rain shadows can also develop on the lee side of significant topographic features. As for storm type, summer precipitation derived from convective thunderstorms is characterized by greater spatial variability than winter precipitation from frontal storms (Noy-Meir 1973, Whitford 2002). The size of precipitation events is also an important attribute of dry-region precipitation regimes (Noy-Meir 1973, Sala and Lauenroth 1982, Ehleringer et al. 2000, Whitford 2002). Event size and timing (seasonal, diurnal, and in relation to antecedent environmental conditions) in combination are important for determining the ecological effects of precipitation.

Precipitation intensity (amount per unit time period) also affects hydrologic partitioning of precipitation. Precipitation intensity, soil characteristics (e.g., texture and antecedent moisture conditions), and ground-surface features (e.g., ground-surface roughness, amount and distribution of ground cover, versus bare soil or bedrock) together determine whether precipitation events result in infiltration or runoff (Whitford 2002, Breshears et al. 2003). Generally, as precipitation intensity increases, a greater proportion of the total rainfall is partitioned to streamflow (Gregory 1916). If precipitation intensity exceeds the soil infiltration rate, runoff will be generated – increasing the potential for soil erosion, debris flows, and flash floods.

Upland Watershed Characteristics - Schumm (1981) described an idealized fluvial system consisting of three zones: (1) watersheds or zones of net sediment production, (2) streams and rivers representing zones of transport of water and sediment from the watershed, through valleys, to, (3) zones of net deposition, such as deltas and alluvial fans (Figure 4). These zones are not as spatially segregated as represented by Figure 4 because in reality there is a rather complex interpenetration of zones. For example, alluvial sediments may be temporarily stored as channel or flood plain deposits within the channel network of a watershed or in the valley of a large river (zones 1 and 2) (Schumm 1981, Benda et al. 2004). Likewise, deltas (zone 3) may be actively eroded as declining lake levels lower local stream baselevels (J. Schmidt, personal communication).

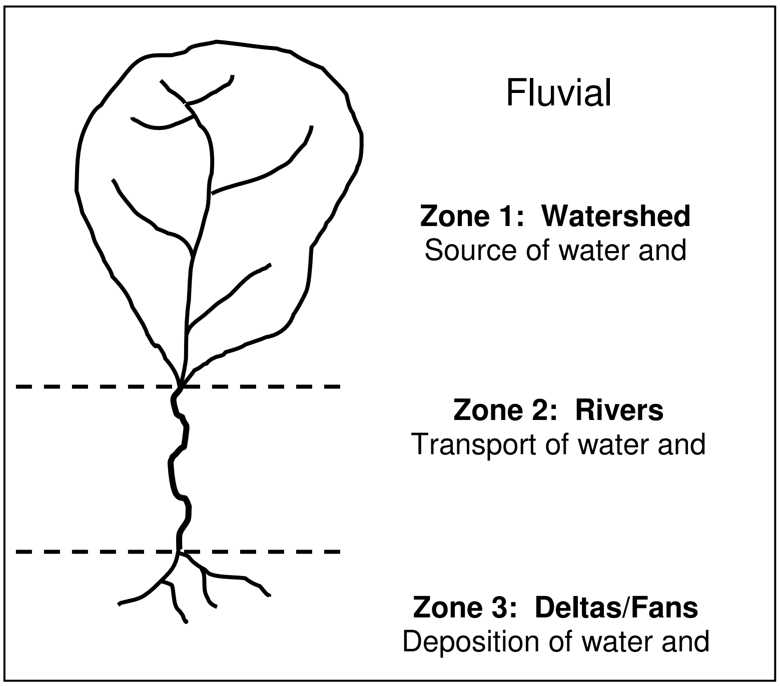


Figure 4. An idealized diagram of a fluvial system featuring: (1) a zone of sediment production (watershed); (2) zone of transport (rivers and streams); and (3) zone of deposition (alluvial fans and deltas). From Scott et al.

The upland watershed contains a diversity of landform features including drainage divides, hillslopes, stream channels and flood plains. Water and sediment are ultimately derived from the upland watershed (zone 1) through the interaction of the nine watershed variables listed in Table 1. The four independent variables of time, initial relief of the watershed, geology, and climate influence the type and cover of vegetation, watershed topography, which in turn influence the runoff and sediment flux from the watershed, the development of stream network and hillslope morphologies, and thus the discharge of sediment and water to receiving streams and rivers (zone 2). The amount and timing of flow and the amount and size of sediment, delivered from thewatershed to the valleys, establishes channel and flood plain form and processes, which provides the physical template for aquatic and riparian ecosystems (Frisell et al. 1986).

Given the number of interactive controlling variables, watershed characteristics can be endlessly diverse. However, regional characteristics allow some generalized inferences about the influence of watershed characteristics on streamflow patterns and sediment flux. In the Southern Plains, thunderstorm events deliver high precipitation rates that cannot infiltrate the soils of typical watersheds, and short duration overland flow events are characteristic of the monsoon season. Land use activities like livestock grazing that increase the area of exposed bedrock, or which decrease soil stability and infiltration rates, result in increased delivery rates of water to stream channels, which in turn lead to more rapid runoff and larger flood events. High surface runoff rates tend to increase soil erosion, and the removal of vegetation also leads to soil erosion by raindrop impact. Delivery of larger amounts of water and sediment from the watershed (zone 1) to stream channels (zone 2) has the potential to alter channel form and process and thus alter riparian and aquatic ecosystems.

W.2.2. Stream Ecosystem Function under Natural/Desired Conditions

Chapin et al. (1996) defined "...a sustainable ecosystem as one that, over the normal cycle of disturbance events, maintains its characteristic diversity of major functional groups, productivity, and rates of biogeochemical cycling" (Chapin et al. 1996:1016). The latter are determined by four "interactive controls" – climate, soil-resource supply, major functional groups of organisms, and disturbance regime (Dale et al. 2000). Streamflow regime, stream geomorphology, and instream habitat, the major 'soil-resources' influencing stream ecosystem function, are described in this section, followed by a discussion of the role of stream biotic functional groups and stream ecosystem dynamics under natural/desired (sustainable) conditions. The attributes and functioning of SOPN stream ecosystems under natural/desired conditions are summarized in Figure 5.

W.2.2.1. Streamflow Regime

Streamflow originates from precipitation falling within a watershed. However, resulting streamflow patterns (streamflow hydrographs) can vary greatly across a watershed due to differences in local climatic conditions, geology, topography, soils and vegetation cover. Precipitation reaches a stream through various pathways, including direct precipitation, unsaturated or Horton overland flow, ground-water flow, shallow subsurface flow, and saturated overland flow (Figure 6) (Dunne 1978). Each of these flow paths respond differently to precipitation events (rain or snow) and thus contribute differentially to two important components of streamflow - baseflow and stormflow. Because rates of groundwater flow are slow and flowpaths are relatively long, water moving to streams along these paths contribute to the baseflow of streams between precipitation events. Surface runoff from precipitation reaches streams more quickly, contributing to stormflow during and shortly after precipitation events (Figure 7a). Because of the potential for high intensity rainfall events, thin, patchy soils, exposures of relatively impermeable bedrock, and sparse vegetation, the hydrographs of Southern Plains streams are dominated by relatively high-magnitude, short-duration, temporally unpredictable stormflow hydrographs with little or no baseflow (Figure 7b). In contrast, larger extraregional rivers in other areas of the country feature snowmelt hydrographs with temporally predictable, longer-duration snowmelt peaks and baseflow (Figure 7c). Streamflow regime determines the mechanical forces available in a valley to erode, transport and deposit sediment and maintain channel form and channel processes.

Temporal (seasonal) variations in streamflow are important in maintaining the ecological integrity of aquatic and riparian ecosystems. The natural flow regime paradigm holds that natural flow variability is primarily responsible for structuring and maintaining the physical and biotic integrity of aquatic and riparian ecosystems (Richter et al. 1996, Stanford et al. 1996, Poff et al. 1997).

Ecologically relevant elements of streamflow include the magnitude, frequency, duration, timing, and change rate of flow. These elements have been used to describe regional streamflow patterns, which vary as a function of climate and watershed characteristics (Poff and Ward 1989). They may also be used to characterize specific hydrologic events, such as extreme high or low flows, or human-modified flow patterns, both of which can exert lasting influence on the ecological integrity of aquatic and riparian systems (Richter et al. 1996).

Although extreme flow variations can eliminate species (Zimmerman 1969, Bain et al. 1988), episodic floods and droughts are necessary for persistence of some species of fish (Meffe 1984) and plants (Nilsson et al. 1991, Friedman et al. 1996). In fact, the high biological diversity of

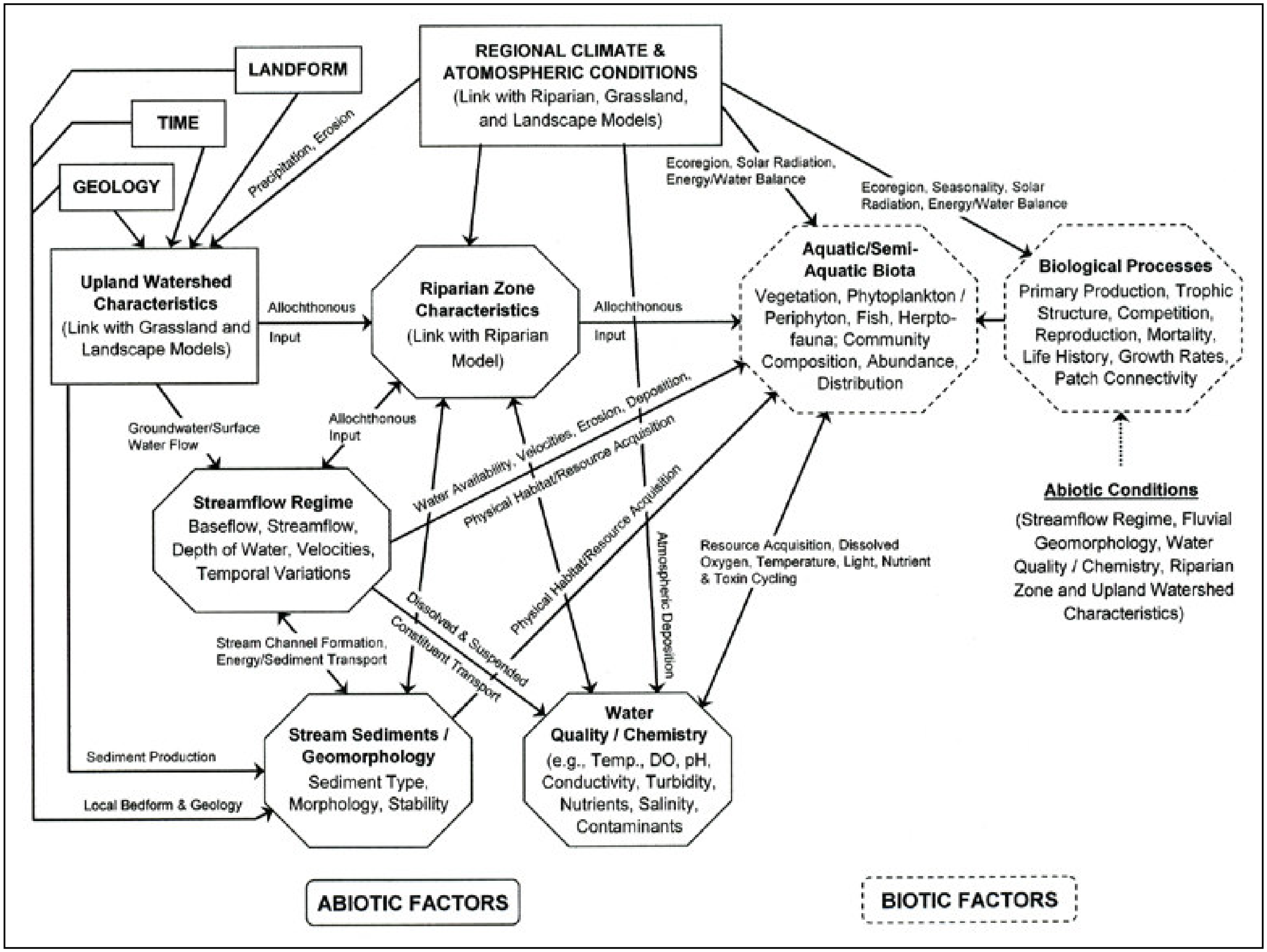


Figure 5. Natural/desired stream ecosystem function. Modified from Scott et al. (2005).

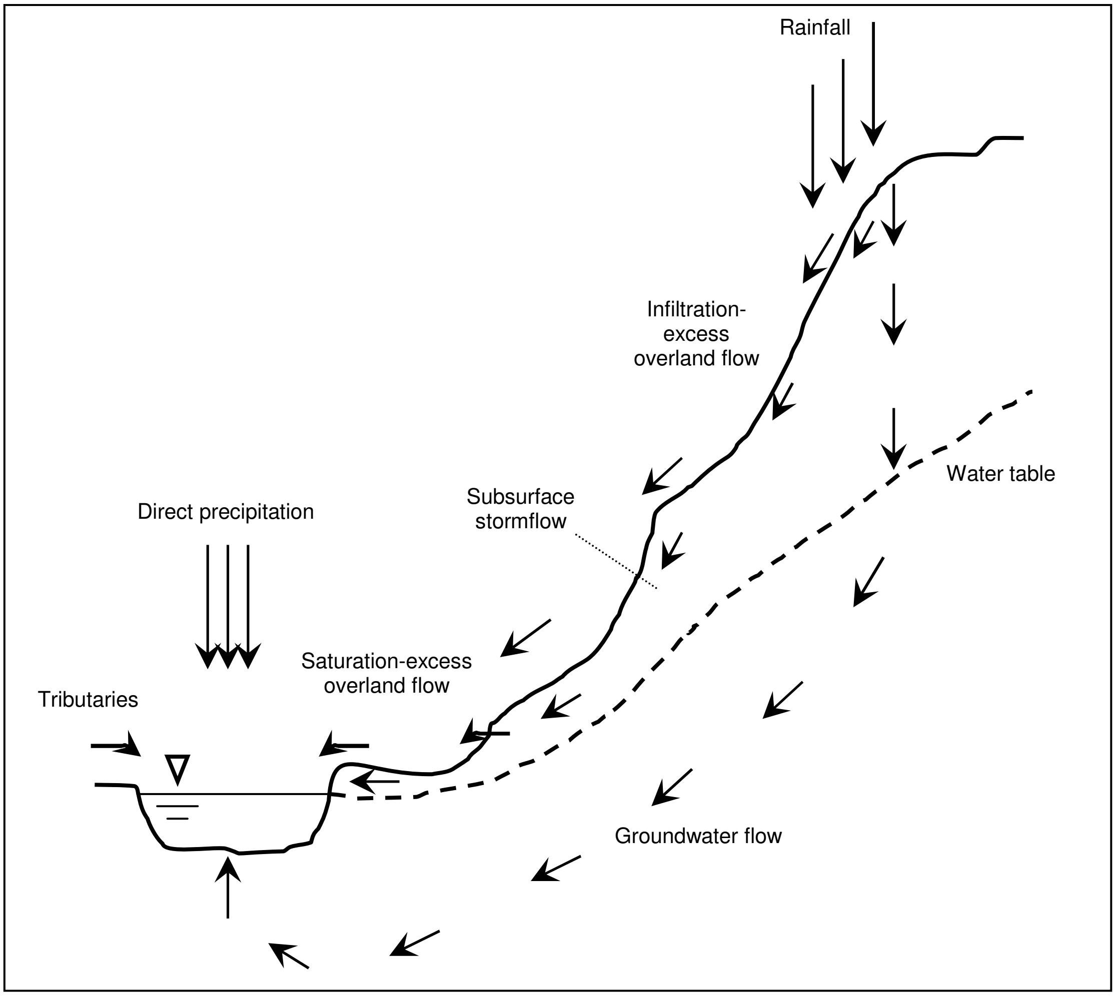


Figure 6. Idealized flow paths from a watershed to a stream. Adapted from Scott et al. (2005), after Dunne (1978) and Ziemer & Lisle (1998).

riverine ecosystems may be attributable to relatively frequent hydrologic disturbance events, which would act to limit the process of competitive exclusion of species (Huston 1979).

Given the importance of flow variability in structuring and maintaining aquatic and riparian ecosystems, identification of a parsimonious set of hydrologic indicators that are sensitive to anthropogenic disturbances, would be an important element of any efforts to monitor, manage, and restore aquatic and riparian ecosystems (Olden and Poff 2003).

W.2.2.2. Stream Sediments/Geomorphology

Stream channels adjust to variations in streamflow and the size and amount of sediment supplied to the stream from the watershed. Flow governs channel dimensions such as width, depth and meander pattern, as well as the amounts of bed load (sands and gravels) and suspended load (silts and clays) carried by the stream. Channel form is mostly determined by the amount and size of bedload, even where bedload is a small portion of the total sediment flux. Schumm (1981) has identified five general channel types based on plan-view pattern and channel stability, the latter a function of sediment size, sediment load, flow velocity, and stream power (Figure 8).

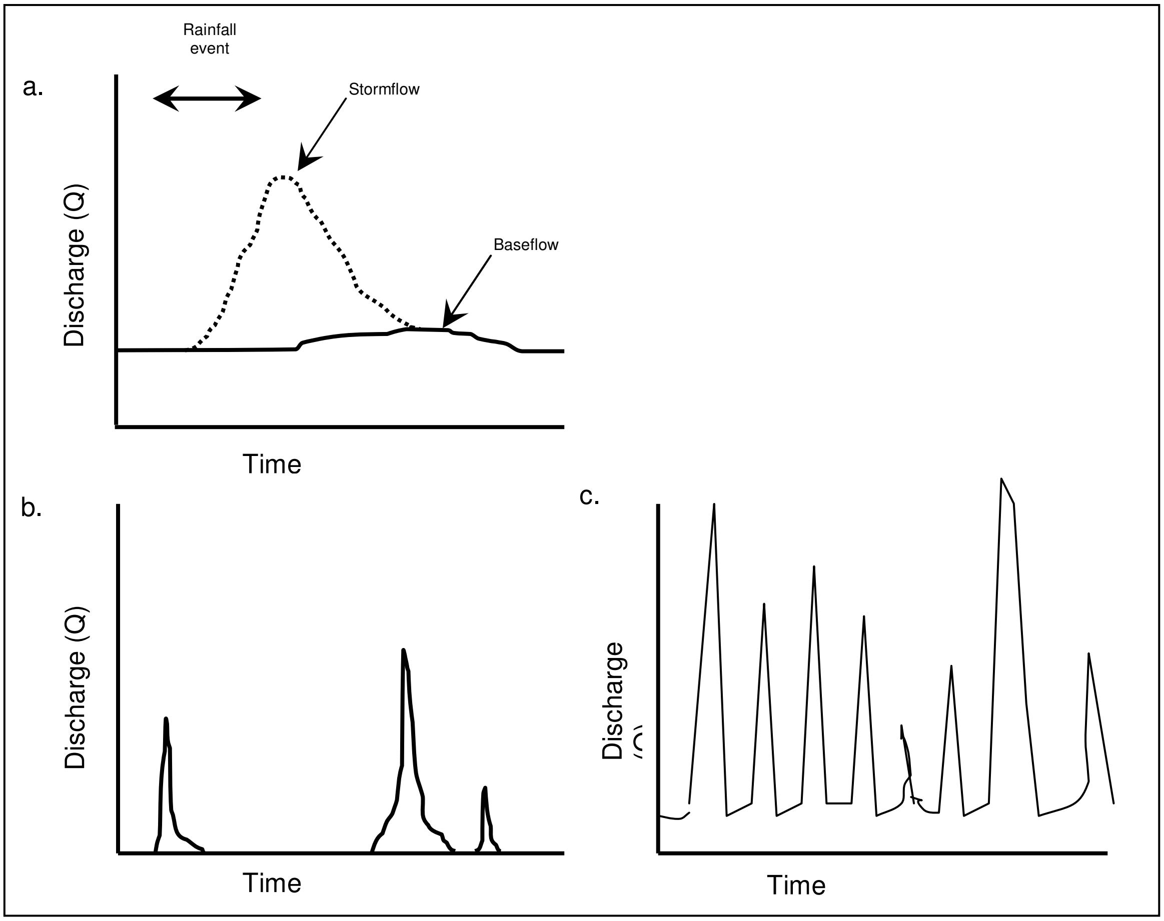


Figure 7. Stream hydrographs. (a) Idealized relationship between stormflow and baseflow components of a stream hydrograph for a discrete rainfall event. (b) Idealized hydrograph of an ephemeral stream featuring highly variable and temporally unpredictable peak flows. (c) Idealized hydrograph of an unregulated, large perennial stream featuring variable but temporally predictable seasonal peak flow (from Scott et al. 2005, modified after Dunne 1978).

An alternative stream classification system has been proposed by Rosgen (1996) based on channel pattern (single, braided, or anastomosed channel configuration, sinuosity, and meander width ratio), channel slope, width/depth ratio, entrenchment ratio, channel materials, and additional parameters quantifying the condition and stability of streams (Figure 9). Stream classification is used to anticipate the response of a stream to changes in streamflow, sediment load, and other stresses (e.g., bank stabilization, channel straightening, and instream structures) given stream type. Since the impact of stream geomorphology and changes in stream geomorphology on aquatic and riparian habitat are great, periodic, albeit infrequent, geomorphic surveys of representative stream reaches (both perennial and ephemeral) in SOPN parks would be an important element of any effort to monitor, manage, and restore aquatic and riparian ecosystems.

Effects of Stream Geomorphology on Instream Habitat - Associations among biological stream communities and habitat characteristics at various spatial scales have been well described in recent studies (Lyons 1996; Lohr and Fausch 1997; Maret et al. 1997; Brown 2000; Waite and Carpenter 2000). Important physical habitat factors include flow regime, substrate, and

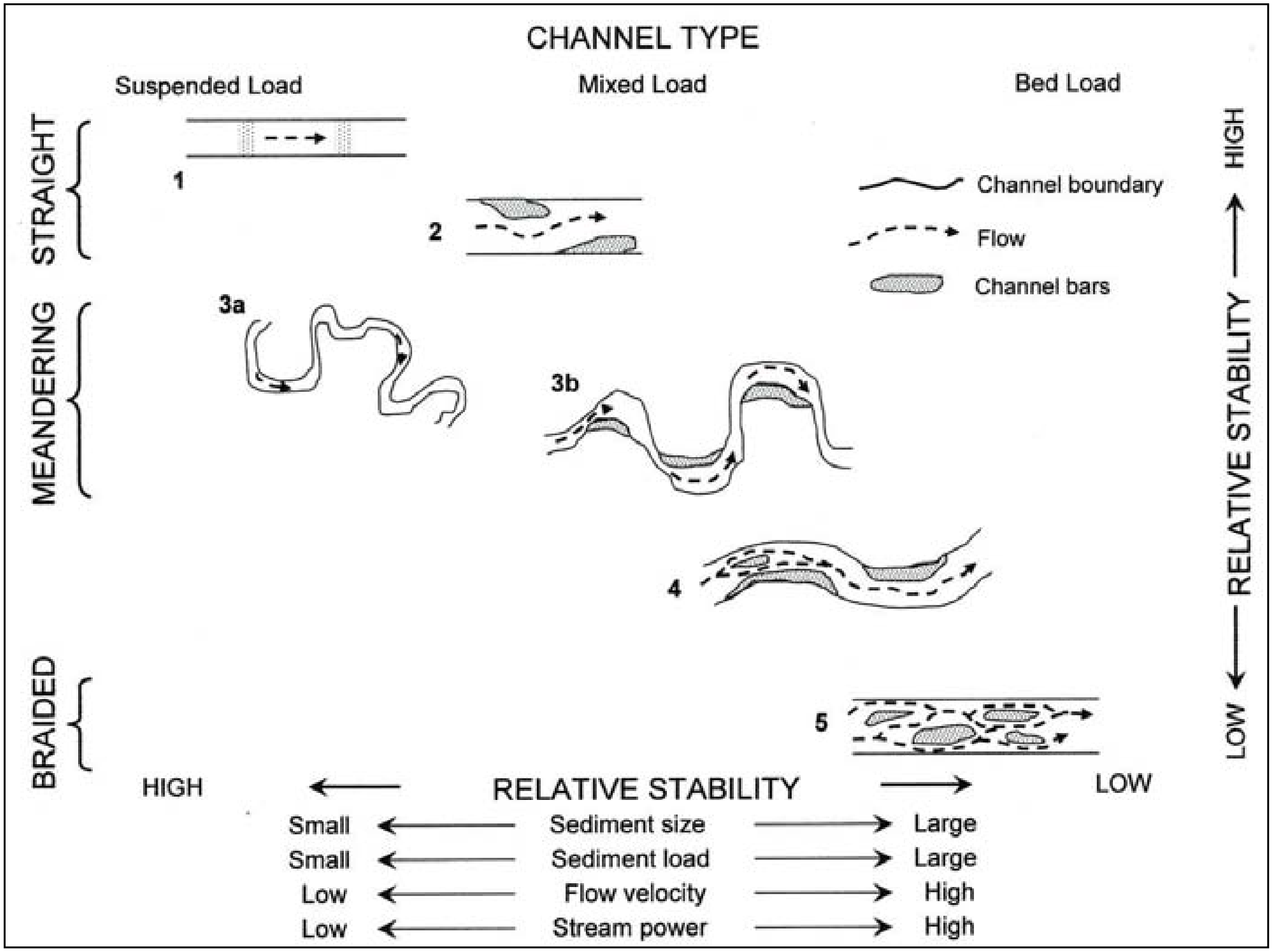


Figure 8. A qualitative classification of stream channels based on pattern (straight, meandering, or braided) and type of sediment load, along with flow and sediment variables and stability (level of erosional activity). From Scott et al. (2005), after Schumm (1981)

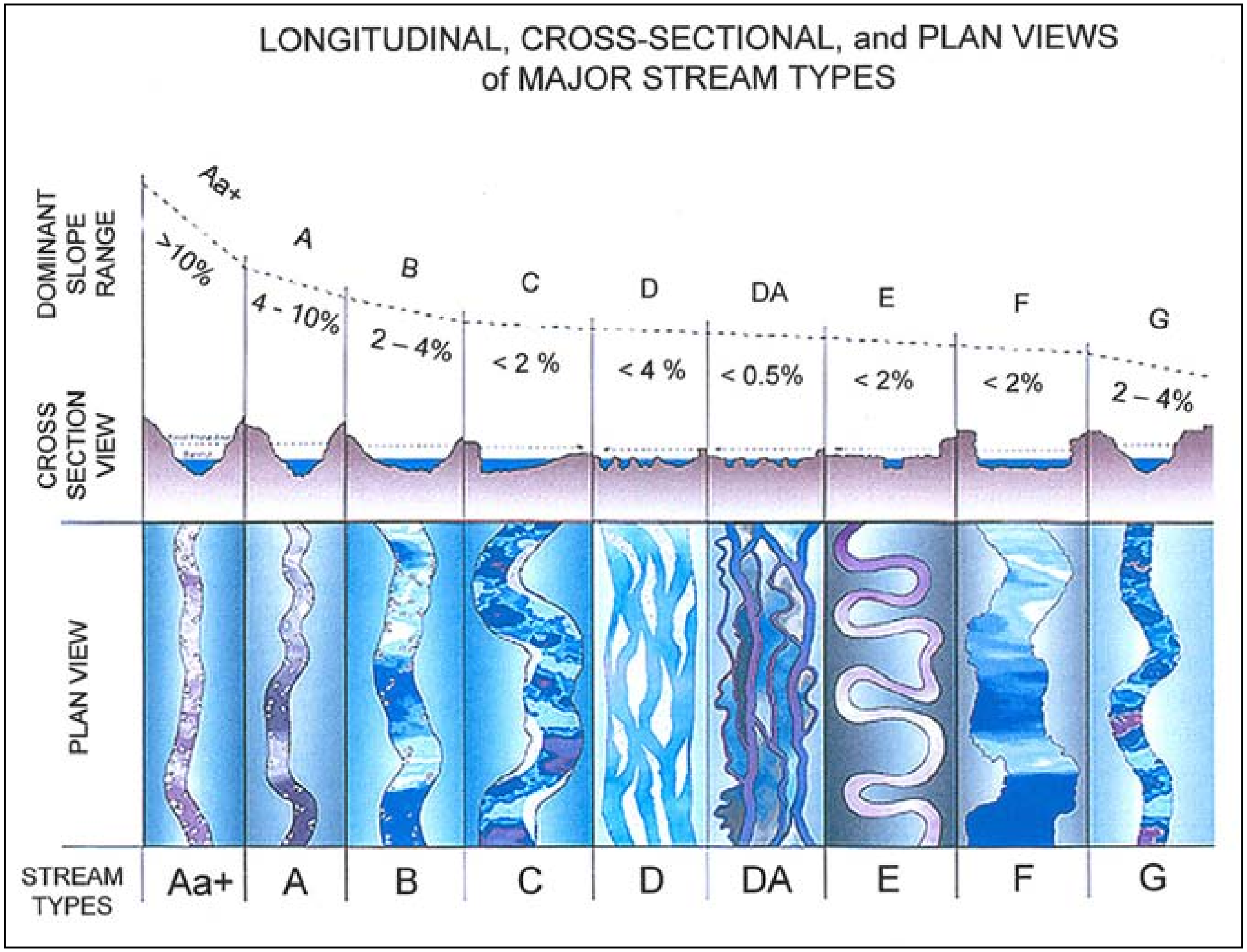


Figure 9. Broad level stream classification based on channel slope, channel shape (cross-section geometry), and channel pattern (sinuosity, meander width ratio, and single, braided, or anastomosed channel configuration). From Rosgen (1996).

temperature (Allan 1995). In unaltered systems, dissolved oxygen is rarely limiting, but can become a critical environmental variable in altered (polluted or diverted) systems (Allan 1995).

Flow regime is an important determinant of aquatic community structure. Flow regime can affect macroinvertebrates both directly (physiological and morphological adaptations) and indirectly (through its effects on algae and fish). The majority of studies assessing the impacts of streamflow have focused on fish. For example, Brown and Ford (2002) demonstrated the importance of natural flow regime on the spawning success of native fishes in the Tuolumne River in California. Altered flow regimes often favor introduced fish species that are generalists and can tolerate a wide array of environmental conditions (Meador et al. 2003). Because of their different feeding habits, introduced fish can alter macroinvertebrate community structure (McDowall 2003). Other studies have demonstrated that when flows are reduced, fish taxa richness is also reduced (Cuffney et al. 1997).

Additionally, streamflow is a determinant of stream width and depth and the formation of features such as pools, riffles, wide meander loops, and sand bars – important microhabitat for aquatic biota (Gordon et al. 1992). Water velocity is a factor in determining the distribution of microhabitats (Munn et al. 2002) and thus plays a role in influencing benthic community structure. Habitat homogenization, which reduces the number of microhabitats, can have detrimental impacts on native stream biota. For example, several native fish in California streams require riffles for successful spawning (Brown 2000). Today, these native fish are only found at upper tributary sites because anthropogenic modification has eliminated downstream riffle habitat and non-native fish now occupy the disturbed areas (Brown 2000). Microhabitat diversity is necessary for the survival of some species, and may vary seasonally. For example, Baltz et al. (1991) found that rainbow trout (*Oncorhynchus mykiss*) require slower, deeper reaches of stream when temperatures are cool. Although macroinvertebrate community structure was not examined in these studies, it is likely that macroinvertebrate communities also changed in response to abiotic (flow regime) and biotic (fish community) alterations.

Direct effects of flow regime and habitat type on benthic macroinvertebrates and algae have also been studied. Algal community structure has been shown to change in response to flow regime (Munn et al. 2002), which can then alter macroinvertebrate communities. In one study, algal decreases resulting from low flow in a Colorado stream resulted in a shift from a collector-gatherer macroinvertebrate community structure to a shredder community structure (Canton et al. 1984). When assessing the effects of environmental stressors and drivers on benthic community structure, it is critical to understand the underlying effects of flow regime on these communities.

Flow regime and parent material determines substrate composition (Allan 1995), which plays a critical role in aquatic macroinvertebrate survival (Thorp and Covich 1991) due to their benthic lifestyle. Substrate provides sites for resting, food acquisition, reproduction, and development, as well as refuge from predators and physical conditions. A sharp distinction occurs between the types of fauna found on hard streambeds (bedrock or boulder) and those found on smaller substrate (Gordon et al. 1992). Different groups of macroinvertebrates require different substrate types and microhabitats. These groups also play different functional roles in their environment. For example, “bioturbators,” such as oligochaetes and crustaceans, live in fine sediments, mix organic matter, and stabilize soil structure, whereas “shredders,” such as stoneflies, shred organic matter and prepare it for decomposers (Freckman et al. 1997). In general, diverse substrate characteristics promote diverse taxonomic assemblages. The diversity and abundance of aquatic macroinvertebrates increases with substrate stability and the presence of organic detritus (Allan 1995).

W.2.2.3. Water Quality/Chemistry

Water temperature varies seasonally and daily from one location to another due to differences in climate, elevation, the extent of streamside vegetation, and relative contributions of groundwater to streamflow (baseflow). The temperature of large rivers is less likely to be affected by shading, as their size conveys thermal inertia and large portions of the river are exposed to the sun (Allan 1995). In small streams typical of SOPN parks, however, shading can play an important role in regulating water temperatures. Many anthropogenic activities (stressors), such as grazing, roads, and stream channelization, can remove riparian vegetation along banks and consequently eliminate shading.

Temperature affects the growth and respiration of individual organisms and the productivity of ecosystems through its influence on metabolic processes. Organisms generally perform best within the subset of possible temperatures that corresponds to an unaltered habitat in their location (Allan 1995). Baltz et al. (1987) demonstrated the importance of temperature as a control on habitat preference of four fish species in a California stream. Temperature may influence organisms directly or indirectly due to changes in oxygen saturation levels (Thorp and Covich 1991). It has not, however, been determined if the association between macroinvertebrate diversity and temperature is causal or merely coincidental because many biotic and abiotic parameters covary (Thorp and Covich 1991).

The life history characteristics of macroinvertebrates can be altered by changes in water temperature. This results in changes in survival, fecundity, and time of emergence, and can ultimately alter macroinvertebrate species assemblage structure (Vinson 2001). In one case, immediately downstream from a cold-release dam, taxa tolerant of cold water such as chironomids and amphipods were dominate and less tolerant species of the orders Plecoptera, Ephemeroptera, and Trichoptera were uncommon (Stevens et al. 1997). Similarly, if water temperature is increased, native cold-water taxa can be replaced by non-native warm water taxa (Maret 1995). And changes in water temperature also alter algal assemblages (community composition and abundance), leading to changes in macroinvertebrate communities (Stevens et al. 1997).

Due to their influence on habitat quality, certain natural chemical features of aquatic systems significantly affect species composition, abundance, and diversity of macroinvertebrates. Of these chemical features, dissolved oxygen and conductivity (salinity or hardness) are the most important (Thorp and Covich 1991). Increases in salinity and alkalinity and decreases in dissolved oxygen are correlated with decreases in macroinvertebrate density and diversity (Earl and Blinn 2003). Anthropogenic pollution has had a severe impact on the integrity of aquatic ecosystems by altering these chemical parameters, as well as by introducing organic and inorganic toxicants (Thorp and Covich 1991).

W.2.2.4. Stream Biota

Biotic Functional Groups - Chapin et al. (1996) identified biotic functional groups (hereafter described as *functional types*) as one of the four interactive controls of ecosystem sustainability because of the capacity of dominant functional types to shape the structure and functioning of whole ecosystems. Associated with efforts to the model ecological consequences of global climate change, a vast literature has developed concerning different approaches to deriving or classifying functional types – particularly with respect to vegetation (e.g., Smith et al. 1997). Identification and use of a particular functional-type scheme depends on the ecosystem function(s) of interest. It has been proposed that the most important functions in dryland terrestrial ecosystems are those that control the retention of water and nutrient resources because productivity and diversity cannot be sustained in systems that fail to retain resources (Ludwig and Tongway 1997, Whisenant 1999, Whitford 2002). Because of their landscape position and highly connected linear forms, aquatic and riparian ecosystems receive large fluxes of water and sediment from upland and upstream sources. Similarly, their potential to store flood water and nutrient-rich sediments are considered key functional attributes (Mitsch and Gosselink 1993). Functions affecting the cycling and retention of water and nutrient resources will be emphasized here, but other functions will not be excluded. For purposes of this report, it is less important to adopt a specific functional-type classification scheme than it is to include a broad functional perspective when considering the biotic components of aquatic and riparian ecosystems.

Without adopting a particular classification scheme, it remains useful to identify two general categories of functional types that are equally important for ecosystem dynamics. These are (1) *functional effect types* –organisms with similar effects on ecosystem functions such as primary production, nutrient cycling, and sediment trapping, and (2) *functional response types* – organisms with similar responses to environmental factors such as climate, resource availability, natural disturbances, and water management activities (Walker 1997, Walker et al. 1999, Díaz and Cabido 2001). The distinction between these two types is important for considering how biotic composition affects the resistance and resilience of ecosystems to climatic fluctuations and changes, natural disturbances, and anthropogenic stressors (Walker et al. 1999). Although some workers have emphasized the importance of overall functional diversity for sustaining ecosystem processes (Tilman et al. 1997), the effect-response distinction suggests that long-term ecosystem functioning may be favored when different functional response types are nested within the same functional effect type (Walker et al. 1999, Díaz and Cabido 2001). Thus, functional redundancy and functional diversity may both be important for long-term persistence of ecosystem structure and functioning.

Aquatic / Semi-Aquatic Biota - Aquatic ecosystems include biotic functional groups that fall into four main categories: algae, benthic macroinvertebrates, fish and amphibians. The relative abundance of different types of primary producers (algae) depends on many factors including nutrient availability, water depth and velocity, the stability of the substrate, and disturbance regime. Unshaded streams can support dense algal growth (autochthonous productivity) (Covich et al. 1999), but shaded streams rely more on terrestrial (allochthonous) inputs and algal growth is therefore minimized. Although the function of algal assemblages is similar in both shaded and non-shaded systems, the magnitude of algal contribution is different under these two conditions. Primary producers are the interface between the abiotic and biotic environment because they respond to physical variables and influence biotic communities. Macroinvertebrate “grazers” or “scrapers” consume algae and therefore the type and abundance of algae can strongly influence macroinvertebrate communities. Some studies indicate that an increase in algal abundance is correlated with an increase in macroinvertebrate density and growth, and decreases in algal abundance are associated with reduced macroinvertebrate densities (Feminella and Hawkins 1995).

Benthic macroinvertebrates are a vital link in aquatic and riparian systems. They are a food source for fish, amphibians and birds, and they also play a consumer role as they graze on many algae species (McCafferty 1998, Steinman 1996). Macroinvertebrates are useful indicators of aquatic ecosystem quality and have therefore been used for biomonitoring since the early 1900’s (Cairns and Pratt 1993). Recent efforts focus on the development of indicator species, diversity indices, and multivariate techniques, which link macroinvertebrate communities with habitat conditions. Because conditions such as riparian vegetative structure, geology, and climate determine the state of a stream and therefore the community of organisms that occupy that stream (Townsend et al. 1997), it is also important to understand regional climatic and atmospheric conditions, as well as any drivers or stressors in the system, whether anthropogenic or natural.

Macroinvertebrates respond to physical parameters such as temperature, substrate, and current velocity (Covich et al. 1999) and they are also influenced by their chemical environment, including pH, oxygen availability, and any anthropogenic chemical additions (Johnson et al. 1993). Biotic factors (predation, parasitism, competition) and food availability (the presence or absence of algae or detritus) in a community can also impact macroinvertebrate communities (McCafferty 1998, Power 1990). Macroinvertebrate indicator species can be helpful in determining ecosystem characteristics and can be used to compare different aquatic systems. A good indicator species is sensitive to its physical and chemical environment (Johnson et al. 1993). When the environmental requirements for an indicator species are known, the presence of that species indicates that those requirements have been met.

When using macroinvertebrates to assess stream quality, it is also important to examine communities and populations in addition to specific indicator species. One commonly used index that examines entire community and species assemblages is the Index of Biological Integrity (IBI). The IBI employs metrics of certain characteristics, such as trophic composition, native and non-native species composition, and species diversity and abundance, to determine "scores" that indicate the biological integrity of a given site compared to the integrity of a comparable "least-disturbed" site (Karr 1991). A diverse environment promotes a diverse macroinvertebrate community and a loss of species diversity or abundance, may indicate environmental degradation (Covich et al. 1999). It is important to assess the integrity of a stream system on a site-specific basis, as macroinvertebrate community structure will naturally vary from site to site and across regions. Environmental conditions including physical, chemical, and biological parameters can be used to determine the "least-disturbed" condition of a given system (Covich et al. 1999).

Many different statistical techniques exist to assess stream quality using data describing macroinvertebrate communities. For example, univariate techniques are used to relate macroinvertebrate response to a single variable (i.e. sewage inputs) (Johnson et al. 1993) and multivariate techniques assess the effects of multiple variables on a stream system. Multivariate techniques are especially useful for addressing and discerning between the variety of anthropogenic influences. With the advancement of statistical bioassessment techniques, macroinvertebrates have become an integral part of evaluating stream and watershed quality.

W.2.2.5. Stream Ecosystem Dynamics

Biotic vs. Abiotic Controls - Power et al. (1988) examined the enormous complexity of the influence of abiotic and biotic factors on the structure and functioning of aquatic communities. They concluded that many of these processes are not well understood for stream systems and will require much additional research in order to develop a full understanding of the dynamics involved. Abiotic conditions of the local environment often determine whether stream organisms can colonize or persist in new or changing habitats. Many different abiotic variables or interactive processes may be involved, and in many cases the distributions of stream organisms with respect to physical (abiotic) variables are mediated by interactions with other organisms.

Few ecosystems possess either the frequency or intensity of environmental changes that are observed in stream systems (Power et al. 1988). Seasonal fluctuations in discharge are crucial in the life histories of many fluvial species (Welcomme 1985). As water levels rise and fall, river and stream habitats expand and contract, resource availabilities shift, certain habitats become more or less isolated from others, and flow regimes change, altering other physical gradients (Power et al. 1988). Yet extreme events (such as scouring or dewatering episodes) can eliminate much biota and set the stage for periods of biotic recovery or succession between disturbances (Fisher 1983, Power et al. 1988). Changing water levels play a key abiotic role in structuring stream communities. As water levels rise, the availability of food increases for grazers, insectivores, and detritivores that forage over inundated flood plains. Inundated flood plains also provide nurseries and refugia for many species. The duration of these refuges depends on the hydrograph, channel morphology, and on the ability of various species and size classes to cross barriers under certain hydrologic conditions (Power et al. 1988).

Functional relationships among stream species may change with both density and ontogeny (developmental stage) (Power et al. 1988). Most aquatic species are omnivorous, at least during a portion of their life cycle, and derive their energy and elemental constituents from several trophic levels. Webs of direct and indirect interactions link disparate taxa within channels and radiate through the riparian zone to the divides between catchments (Hynes 1975) or even into adjacent watersheds (Power et al. 1988). It can be argued that streams are abiotically controlled since physical disturbance, a continual stressor, maintains populations at such low densities that biotic interactions are not important. However, biotic interactions may be important in allowing populations to endure abiotic disturbances (Power et al. 1988). In fact, the relative importance of abiotic and biotic factors controlling stream community structure and function may shift with dynamic changes in density of organisms and environmental conditions (Power et al. 1988).

River Continuum Concept - The river continuum concept (Figure 10) describes a transition in ecosystem structure and functioning from narrow headwater streams to broad rivers (Vannote et al. 1980). Based on the principles of fluvial geomorphology, the river continuum concept emphasizes gradual adjustments of biota and ecosystem processes in rivers in accordance with gradual downstream changes in hydrologic and geomorphic properties (Benda et al. 2004).

Headwater streams are often shaded by terrestrial vegetation. These plants reduce light availability to aquatic primary producers (algae) and provide most of the organic input to the stream. Leaves and wood (allochthonous input) fall into the stream and are colonized by aquatic fungi and, to a lesser extent, bacteria. The resulting leaf packs and woody debris are consumed by invertebrate shredders that break leaves and other detritus into pieces and digest the microbial particles. As material is carried downstream, some suspended particles are consumed by filter feeders and some material trapped in benthic sediments is consumed by collectors.

As headwater steams merge to form broader streams, the greater light availability supports more instream production (autochthonous productivity), and the input of terrestrial detritus contributes proportionately less to stream energetics. This coincides with a change in the invertebrate community from one dominated by shredders to one dominated by collectors and grazers. The middle reaches of rivers are typically less steep than headwaters and begin to accumulate sediments from upstream erosion. These sediments support rooted vascular plants and a benthic detrital community of collectors. The largest downstream reaches are typically deep and slow moving, dominated by collectors and detritivores that live in the sediment.

Nutrient Spiraling - In most ecosystems nutrients can be described as cycling largely in place, with minimal transport. In running waters however, transport must be incorporated into the conceptual framework (Allan 1995). Since the cycle involves downstream transport, it is best described as a spiral. In contrast to terrestrial systems where the longer-lived and larger primary producers on land can store and internally recycle nutrients for years, there is a much more rapid turnover of nutrients and carbon in aquatic systems (Chapin et al. 2002). A number of abiotic and biotic processes influence nutrient spiraling. Some uptake, especially of phosphorus, is by physical-chemical sorption of sediments. High flows reduce the opportunity for biological uptake and increase downstream transport. Low flows, stream channel retention, and interchange between subsurface and surface flows increase opportunities for uptake. In addition to direct uptake by autotrophs and microbes, the biological community affects nutrient dynamics through consumption and egestion, and by a number of microbial transformations. Repeated recycling during downstream transport is a key feature of the nutrient spiraling model.

Network Dynamics Hypothesis - Hierarchically branching river networks interact with dynamic watershed disturbances, such as fires, storms, and floods, to impose a spatial and temporal organization on the non-uniform distribution of riverine habitats, with consequences for biological diversity and productivity (Benda et al. 2004). Abrupt changes in water and sediment flux occur at channel confluences in river networks and trigger changes in channel and floodplain morphology. Based on the concept of a river network as a population of channels and their confluences, Benda et al. (2004) have developed testable predictions about how basin size, basin shape, drainage density, and network geometry interact to regulate the spatial distribution of physical diversity in channel and riparian attributes through a river basin.

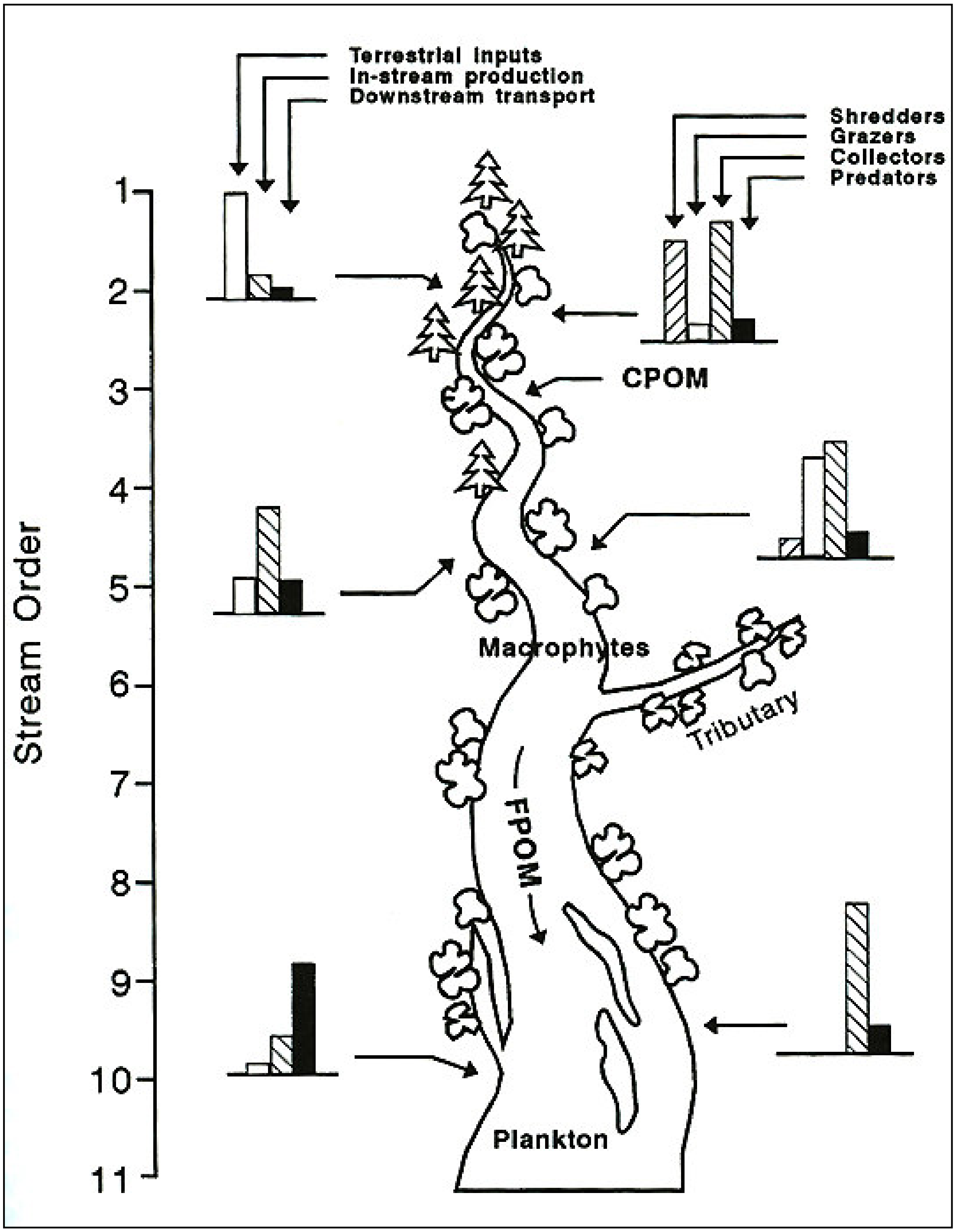


Figure 10. River continuum concept. From Mitsch and Gosselink (2000).

W.2.3. Natural and Anthropogenic Stresses and Stream Ecosystem Response

The success of the monitoring program in detecting the ecological effects of anthropogenic stresses depends on the ability to interpret trends in resource condition against the backdrop of intrinsic variation. Hypotheses concerning the effects of anthropogenic stressors on ecosystem structure and functioning must be grounded in an understanding of the relationship between natural drivers and ecosystem structure, functioning and dynamics. Ecosystems and their components can be characterized on the basis of more structural and functional attributes than can be affordably monitored. Thus an important goal of this model is to guide the identification of a parsimonious set of "information-rich" attributes that provide information concerning multiple aspects of stream ecosystem response and condition (Noon 2003).

This section describes predominant natural and anthropogenic stressors affecting the structure and functioning of stream ecosystems of the Southern Plains, and presents conceptual models of degradational processes related to those stressors. The discussion begins with a description of disturbance regime theory.

W.2.3.1. Disturbance Regime Theory

Disturbance in aquatic ecosystems can be described in terms of frequency, intensity, predictability, time since disturbance, predation intensity, resource variability, and environmental heterogeneity. Responses to both natural and anthropogenic disturbances vary regionally, due to constraints imposed by geomorphic and hydrologic regimes. Three prominent hypotheses explain the role of disturbance on stream community structure: the equilibrium hypothesis, the intermediate disturbance hypothesis, and the dynamic equilibrium hypothesis (Resh et al. 1988).

Historically, the equilibrium hypothesis, which assumes a constant environment, was viewed as the appropriate model for describing community structure. This model assumes that community structure is controlled by biotic processes. Therefore, in the absence of disturbance, community structure is the direct result of competitive, mutualistic, and trophic interactions among species (Resh et al. 1988). In recent years, views on disturbance have moved away from the equilibrium hypothesis and towards the intermediate disturbance hypothesis.

The intermediate disturbance hypothesis (Hutchinson 1961, Connell 1978, Ward and Stanford 1983) suggests that intermediate levels of biotic or abiotic disturbances (e.g., frequency of substrate shifting or periodic flooding events) can promote maximum species diversity under certain circumstances. The intermediate disturbance hypothesis assumes a competitive hierarchy of species. Thus, in the absence of disturbance, superior competitors will eliminate inferior ones, reducing the species richness of a system (Resh et al. 1988). In contrast, if disturbances are too frequent or too large, the resident competitors will be eliminated and colonizing species will dominate the system (Resh et al. 1988). Maximum biotic diversity is maintained in aquatic systems by a level of disturbance that maintains environmental heterogeneity, but also allows biotic communities to become established (Ward and Stanford 1983).

In the dynamic equilibrium model, Huston (1979) suggests that if the recurrence interval of disturbance is shorter than the time necessary for competitive exclusion, then species that are poorer competitors will persist, increasing species richness in the system. In some cases, however, disturbance can be severe or frequent enough to eliminate species with long life cycles. This model allows for the differentiation between rarely disturbed systems with equilibrium conditions, and those with "opportunistic" community types associated with frequent disturbance (Resh et al. 1988), among which are a number of SOPN streams. In an example of one such system, Reice (1985) found that frequent disturbances kept the macroinvertebrate community in perpetual disequilibrium, always responding to the latest event. Frequent disturbance prevented competitive exclusion in this case, resulting in high species richness.

W.2.3.2. Streamflow Alteration

Streamflow variability is the principle force that creates and maintains the integrity of stream ecosystems (Brinson et al. 1981, Poff et al. 1997, Bunn and Arthington 2002). Thus, any anthropogenic activity that disrupts the natural flow regime represents a significant threat to the structural and functional integrity of these ecosystems, both directly and indirectly. Large, in-channel dams have significantly altered riverine ecosystems throughout the western United States by disrupting the flow of water and sediment and fragmenting once-continuous aquatic and riparian corridors. Because water storage behind dams is large relative to runoff, the alteration of aquatic and riparianecosystems is correspondingly greater in this region (Graf 1999). Diversions and dams affect regional streams that enter all SOPN parks. The geomorphology of streams changes in response to alterations in streamflow.

Channel adjustments, involving changes in cross-sectional form, the size and distribution of bed and bank materials, slope and planform, accompany streamflow alteration and reflect complex adjustments to temporal variations in streamflow and the amount and size of sediment particles supplied to the stream from the watershed. Complex interactions among flow, channel response, and plant and animal life history contribute to considerable spatial and temporal variability in the response of aquatic and riparian ecosystems. Biotic changes typically show a lagged response to driving physical variables, frustrating efforts to develop simple predictive models of ecosystem response (Petts 1987). This suggests the potential importance of using measures of physical processes or attributes, like channel form, as leading indicators of degradational change in stream ecosystems.

Flow Depletion - Flow depletions resulting from the diversion of streamflow, can have a range of effects on aquatic and riparian ecosystems. Concerns about the effects of water abstractions on spring, stream, and river biota are not limited to surface water abstractions. Groundwater abstractions for municipal and agricultural uses can also alter aquatic communities (Erman and Erman 1995, Armitage and Petts 1992). Flow reduction due to groundwater withdrawal can generally have the same physical results as flow reduction through surface water diversions. Biotic community alterations have been observed in response to groundwater withdrawal (Wood and Petts 1994, Bickerton et al. 1993), but studies are scarce. Despite the lack of studies that directly examine community structure in response to groundwater withdrawal, it is known that groundwater inputs provide important nutrients that are not readily available in surface-water dominated streams (Dahm et al. 2003). These nutrients can be important to stream biota such as algae, which in turn shape macroinvertebrate community structure (Dahm et al. 2003).

Altered Flow Variability - Physical changes resulting from flow alteration downstream of dams typically degrades the biotic integrity of stream ecosystems by altering habitats and competitive interactions in favor of non-native aquatic and riparian species. Native fish and macroinvertebrate species have evolved life-history characteristics specifically adapted to natural flow regimes (Bunn and Arthington 2002). In the west, flow variability is a critical component of natural flow regimes. Streamflow alterations can result in an increase or decrease of baseflow, a change in flow patterns (especially peak flows), and the conversion of intermittent to completely dry reaches (Vinson 2001, Weisberg et al. 1990, Blinn et al. 1998). Flow alteration can negatively affect native species with specific flow adaptations and requirements, while increasing opportunities for the establishment of non-native species that tolerate relatively regulated flows (Blinn et al. 1998, Bunn and Arthington 2002, Haden et al. 2003). This leads to changes in species composition, diversity, abundance, and the density of fish, macroinvertebrates, and algae communities (Weisberg et al. 1990, Castella et al. 1995, Benenati et al. 1998). Dry stream channels also prevent movement between stream sections which impacts species dependent on stream connectivity for population maintenance (Bunn and Arthington 2002). In addition to the direct effects of changes in flow regime, changes in macroinvertebrate communities may be the result of changes in fish or algal communities.

Algal communities can be significantly altered by disturbances such as dams, as well as grazing and agriculture (Shannon et al. 1994, Haefner and Lindahl 1991). Changes in algal community structure are followed by changes in the macroinvertebrate community. The biochemical, physiological, morphological, and life-history characteristics of a macroinvertebrate are indicative of the state of the environment in which it occurs (Johnson et al. 1993). Physical deformities and life-history characteristics (survival, growth, and reproduction) can be examined to assess habitat quality (Johnson et al. 1993). Abnormal biochemical, physiological, morphological, and life-history characteristics are associated with an influx of toxins to a system (Johnson et al. 1993).

The status of native fish communities is a high priority vital sign for many NPS I & M Networks. Macroinvertebrates are an important food source for fish, thus influence fish community structure. Predation by fish, in turn, influences macroinvertebrate communities. Because these trophic levels are dependent on each other, disturbance to one affects the other. For example, mining, dams, non-native species establishment, flow reduction, trampling, and organic pollutants negatively affect both macroinvertebrate and fish communities (Minckley and Deacon 1968, Diamond and Serveiss 2001, Sappington 1998, Matta et al. 1998, Shannon et al. 1996, Woodward et al. 1994, Canton et al. 1984).

Damming of streams and rivers can also alter macroinvertebrate community structure by altering instream temperatures. Temperatures may either decrease or increase depending on where (what elevation) water is drawn from a reservoir (Vinson 2001, Benenati et al. 2000). Altered temperature can affect macroinvertebrate community structure because life-history characteristics such as fecundity, growth rate, survival, and time of emergence are regulated by water temperature (Vinson 2001). These temperature alterations can be detrimental for some species and favorable for others, creating a changed community structure that has lower taxa richness and may not recover quickly, even if original temperatures are restored (Vinson 2001).

In addition to changes in flow regime and temperature, suspended sediments are often reduced downstream from dams, which can cause changes in fish and macroinvertebrate community structure (Blinn et al. 1998, Stevens et al. 1997). Communities that exist before flow regulation are typically characterized by species that are tolerant of high sediment loads. These same conditions inhibit autochthonous (algal) productivity and favor allochthonous inputs from terrestrial organic material (Haden et al. 2003).

Floods and Drought - The effects of extreme flow events on benthic communities depend on both precipitation and the hydrogeologic characteristics of a given watershed. Scouring floods may enhance co-existence of species by maintaining an intermediate level of disturbance. Where climatic, geologic, or anthropogenic factors decrease the permeability of catchment soils and eliminate intermediate storage compartments for water, discharge can fluctuate extremely and abruptly, resulting in scouring episodes that destroy biota (Power et al. 1988). Drought also acts as an extreme disturbance event. Many stream species have adapted resistance to flooding and drought events, including physiological and behavioral adaptations. While these disturbance events can alter community structure in streams, such events are also critical to the life histories of many stream organisms.

The effects of regional climatic drought on aquatic ecosystems are expressed most directly through reduced surface flows and depletion of alluvial groundwater aquifers. Thus, the stress effects of naturally occurring drought mimic those produced by anthropogenic stressors such as damming and diversion of streamflow, groundwater pumping, and channel incision resulting from altered flows of water and sediments, bank stabilization, stream channelization, or in-stream gravel mining (Bravard et al. 1997, Kondolf 1994, 1997, Rood et al. 1995, Stromberg et al. 1996, 1997, Scott et al. 2000).

W.2.3.3. Alteration of Stream Geomorphology

Stream Channelization - Stream channelization is typically carried out to improve drainage or flood-carrying capacity, resulting in a smooth uniform channel with enhanced water conveyence and more predictable hydraulic behavior. The straightening of channels and reduction in roughness leads to greater flow velocities and higher erosive forces, resulting in increased turbidity and sedimentation (Gordon et al. 1992). Excessive siltation of gravel and cobble beds can lead to suffocation of fish eggs and aquatic insect larvae, and can affect the density and composition of periphyton (algal) communities (Gordon et al. 1992). Suspended sediments reduce light penetration and consequently primary productivity. Stream channelization is frequently accompanied by removal of riparian vegetation, changing the relative contribution of allochthonous and autochthonous nutrient sources to the system. A decrease in canopy cover can also result in increased water temperatures and daily temperature fluctuations. Large algal blooms and daily temperature fluctuations are accompanied by large daily fluctuation in oxygen concentrations.

Changes in Channel Morphology Due to Land Use Changes and Instream Structures - Abrupt changes in channel pattern, from straight through braided forms, can occur in response to a range of factors, as critical geomorphic thresholds are exceeded by changes in external variables such as stream power, channel gradient, and sediment (Schumm and Kahn 1972). Such channel pattern-shifts can be triggered by episodic events, which may have long-lasting effects on stream and valley morphology, erosional and depositional processes, and aquatic and riparian ecosystems. Rare, large floods have eroded flood plains and terraces and transformed meandering channels near the threshold of pattern-change to a braided pattern. Subsequent channel narrowing and re-establishment of a meandering channel form can then occur through the process of flood plain construction and the establishment of riparian vegetation on portions of the former channel bed (Schumm and Lichty 1963, Friedman et al. 1996). Channel narrowing can also result from the widespread establishment of tamarisk, observed at many locations in the west. However, more often than not, significant changes in stream morphology (and habitat) are the result of changes in local land use (e.g., grazing practices) or small instream structures such as check dams and low-water bridges.

Alteration of Stream Substrate - Flow diversion, erosion, or trampling by livestock can reduce substrate and species diversity. Substrate embeddedness (increased siltation) can result in a lower diversity of fish and macroinvertebrate species, along with a change in algal assemblages (Cuffney et al.1997). A study of macroinvertebrate communities in the Gore Creek Watershed, Colorado revealed low species abundance at sites with high sediment loads (Wynn et al. 2001). However, many aquatic plants (macrophytes) may prefer finer substrates and, once established in these reaches, act as substrate for other organisms (Gordon et al. 1992). In general, diversity and abundance of aquatic macroinvertebrates have been shown to increase with substrate stability and the presence of organic detritus (Allan 1995).

W.2.3.4. Ungulate Grazing and Trampling

Livestock Grazing - Livestock grazing is one of the most pervasive human stressors of natural ecological systems in the western United States. Livestock use is permitted in portions of one SOPN park (Lyndon B. Johnson National Historical Park), occurs on lands adjacent to most SOPN parks, and in the upland watersheds of all network parks. Most parks in the SOPN were grazed by domestic livestock at one time, and many parks have on-going issues associated with the persistent legacies of past livestock grazing and livestock-management practices.

Heavy grazing on uplands compact soils, which reduces infiltration of precipitation and increases the delivery of water and sediment to streams. The combination of increased upland runoff and reduced channel stability within riparian zones contributes to increased stream bank and channel erosion, and has been implicated in the initiation of channel incision at many locations (Brinson et al. 1981, Cooke and Reeves 1976).

Livestock grazing also increases nutrient loading, alteration of riparian vegetation (which changes instream light and temperature regimes), and increases bacterial inputs (Scrimgeour and Kendall 2003, Davies-Colley et al. 2004). These changes directly and indirectly alter benthic macroinvertebrate communities. Nutrient loading contributes to greater algal growth and a potential subsequent change in species composition. Increased algal growth results in greater invertebrate biomass (Behmer and Hawkins 1986) and a change in community structure (i.e. a change from allochthonous communities to autochthonous communities).

Scrimgeour and Kendall (2003) found a greater total invertebrate biomass at grazed sites vs. non-grazed sites. Non-grazed sites, however, had a greater biomass of shredders (indicative of an allochthonous community) as compared to grazed sites, which had a greater biomass of collectors and scrapers (indicative of an autochthonous community). This is consistent with the expected invertebrate community structure following decreased bank vegetation and increased nutrient loading (Scrimgeour and Kendall 2003). Haefner and Lindahl (1991) studied the effects of grazing at Capitol Reef National Park and found algal growth increased in response to nutrient inputs, followed by selective increases in macroinvertebrate species. Effects of nutrient inputs from livestock urine and feces can also be particularly detrimental to isolated pools which can become anoxic (Haefner and Lindahl 1991). The use of macroinvertebrates as indicators of nutrient related degradation associated with grazing could be a useful tool to assess the magnitude of the impacts on aquatic systems.

Livestock Trampling - Trampling of stream banks by livestock causes a loss of bank stability and changes channel morphology because overgrazed streams become wider and shallower (Scrimgeour and Kendall 2003). Increases in turbidity and suspended solids are also associated with livestock trampling (Davies-Colley et al. 2004). Trampled riparian areas are characterized by soil compaction, vegetation removal, and decreased water infiltration rates, which results in increased runoff rates (Trimble and Mendel 1995). A combination of vegetation loss and wider, shallower streams increases light and water temperature and often results in increased algal growth.

Increases in turbidity, erosion, and suspended solids, however, would decrease light penetration and decrease the growth of algae. These contrasting effects on algal communities make it difficult to predict macroinvertebrate community structure without determining which stressors are dominant in a given situation. In either case, macroinvertebrate diversity typically decreases in response to increasing sedimentation (Kaller and Hartman 2004), followed by an increase in generalist species and a loss of specialist species. For example, Weigel et al. (2000) found that stream reaches with minimal trampling impacts contained more specialist macroinvertebrate species than did stream reaches with greater trampling impacts. Also, species that prefer fine sediments as opposed to coarser sediments (e.g. oligochaetes and chironomids) tend to be found in trampled areas (Meadows 2001). Effects of trampling by livestock in streams and pools across the Southern Plains should be similar to those in other areas, although few studies have examined these effects.

W.2.3.5. Recreation

Visitor use in and around park aquatic and riparian resources tend to be spatially concentrated, magnifying the potential impacts to these systems. Documented impacts from recreation include bank erosion, contamination from human waste, trash, and trampling of plants (Carothers et al. 1976).

At some SOPN parks, recreational activities include driving off-road vehicles through canyons and on river banks (e.g., Reservoir Meredith National Recreation Area), both of which can involve stream crossings and driving up stream channels. As with cattle trails, off-road vehicle trails breach stream banks, increasing hydraulic roughness and removing vegetation. At high flows, turbulence created by these features accelerates erosion, creating more turbulence in a positive feedback loop. Trails and road crossings also serve as preferred flow paths for water onto, and off of the flood plain during rising and falling streamflows, causing further erosion (Trimble and Mendel 1995). Finally, because of reduced resistance to flow, un-vegetated trails crossing flood plain surfaces experience excess erosion during high flows and can trigger channel incision (Cook and Reeves 1976).

Vehicles crossing or driving up streams causes an increase in stream turbidity, total dissolved solids (TDS), total suspended solids (TSS), salinity, and overall erosion (Lane and Sheridan 2002, Sample et al. 1998). Several studies have shown that macroinvertebrate communities respond to these factors. Increased turbidity and the associated decrease in light penetration, result in decreased diversity and/or a complete community shift in both algae and macroinvertebrates (Stevens et al. 1997, Thiere and Schulz 2004). Similarly, increases in TDS and changes in salinity levels can change benthic invertebrate community structure (Leland and Fend 1998). Several studies have demonstrated species-specific responses to TSS, with certain species more resistant than others to high TSS (Thiere and Schulz 2004). Erosion is a direct cause of increases in turbidity, TDS, and TSS, and has been correlated with a decrease in the biointegrity of macroinvertebrate communities where erosion is prevalent (Rothrock et al. 1998). High levels of turbidity, TDS, and TSS inhibit the establishment of light-dependent algae and associated invertebrate assemblages. Sensitive orders such as Ephemeroptera, Trichoptera, and Odonta are found to be less abundant under these conditions (Thiere and Schulz 2004). Instead, more tolerant invertebrate taxa such as dipterans become established (Stevens et al. 1997, Thiere and Schulz 2004).

Off-site roads alter abiotic components of aquatic ecosystems by changing soil density and composition, runoff and sedimentation patterns, light and temperature regimes, and water chemistry (Trombulak and Frissell 2000). Biotic alterations in response to these changes can be seen in riparian vegetation structure, as well as aquatic community structure (Backer et al. 2004). Few studies have examined the direct effects of roads and trails on macroinvertebrate communities. However, macroinvertebrates are sensitive to the effects mentioned above. Kaller and Hartman (2004) found a threshold level of sediment accumulation, above which macroinvertebrate abundance and diversity were reduced significantly. Increased sedimentation also tends to favor macroinvertebrates that prefer habitats characterized by fine substrata such as oligochaetes and chironomids (Meadows 2001). Instream salinity levels are generally greatly increased in the vicinity of roads and certain macroinvertebrate species are more sensitive than others to high levels of road salt (Benbow and Merritt 2004). This sensitivity to road effects makes macroinvertebrate inventories useful for monitoring the status of aquatic systems in national parks where roads have been constructed for visitor access.

W.2.3.6. Altered Fire Regime

Depending on the severity and extent, upland fire events can degrade aquatic and riparian systems due to erosion, increases in suspended and bed-load sediment, and increases in peak flows during floods (Veenhuis 2002, Vieira 2004). Although post-fire impacts may be minimal following low or moderate severity fire, degradation of aquatic and riparian systems following high-severity events can be significant. Erosion rates, for example, following high-severity fire can increase by one or more orders of magnitude (Benavides-Solorio 2003, Moody and Martin 2001).

The structure and function of aquatic and riparian areas are adversely impacted by the sequence of wildfire, increased runoff, erosion and downstream sedimentation. The removal or reduction of the forest canopy, surface vegetation cover and ground cover all contribute to accelerated erosion following severe fire (Cipra et al. 2002). Where present, the loss of forest canopy also reduces shading to riparian areas which can raise water temperatures by 3 to 10 ºC (Amaranthus et al. 1989). A several fold increase in peak flows (due to increased runoff) further amplifies surface and mass erosion (Dennis 1989, Tiedemann et al. 1979). Sediment laden flows often induce sheet wash, rill and gully erosion and can induce mass movements such as debris torrents. As mass movements travel through the channel network, they can cause intense bank scour, which increases the volume of sediment delivered to downstream areas (Cipra et al. 2002).

Alterations to water chemistry following fire also degrade aquatic and riparian systems. The ash from fires can temporarily increase nutrients, ions, turbidity, pH, and alkalinity while decreasing dissolved oxygen levels (Earl and Blinn 2003). Macroinvertebrate densities are reduced immediately after a fire, but can recover within a year, whereas community structure and diversity are affected over a long period (Earl and Blinn 2003, Vieira et al. 2004). Because of intense flooding after burns and because of instream physical and chemical changes, generalist macroinvertebrate species with successful and rapid larval dispersal mechanisms tend to dominate over more specialized macroinvertebrate species that were present in the pre-fire system (Vieira et al. 2004).

W.2.3.7. Non-Point and Point Contaminant Releases

Organic pollutants from pesticide use in urban and agricultural areas act as stressors on instream communities. Macroinvertebrates in stream reaches containing pesticides have shown similar numbers of individuals, but lower overall diversity and richness than communities in pesticide-free reaches (Thiere and Schulz 2004, Lenat 1984). Certain taxa are more sensitive than others to contaminants (Sibley et al. 1991, Thiere and Schulz 2004, Carsten von der Ohe and Liess 2004, Lenat 1984). The effects of different chemicals used for pest control are variable. For example, chemicals which are less water soluble may be less toxic to macroinvertebrates than they would be if they were available in the water column (Schulz and Liess 2001b). Organic contaminants have been shown to negatively affect macroinvertebrate survival and growth, and increase downstream macroinvertebrate drift (Schulz and Liess 2001a). Information about the effects of pesticides on macroinvertebrates is sparse.

Stresses and impacts to streamflow regime, stream sediments and geomorphology, water quality/chemistry, and biota of SOPN streams are enumerated in Tables 2 through 5, respectively, accompaned by indicators of ecosystem response/condition. For each major stressor identified, indicators of ecosystem condition are summarized in Table 6.

W.2.4. Benefits of Stream Classification for Long-Term Monitoring

Indirect effects of climate change and land use practices such as grazing and land-clearing, which degrade upland soil stability and reduce vegetation cover, alter the delivery of water and sediment to receiving streams (Trimble and Mendel 1995). This, in turn, alters the rate, magnitude, and style of channel processes, which ultimately structure and maintain aquatic and riparian ecosystems (Frissell et al. 1986). A hierarchical, process-based approach to geomorphic stream classification offers the possibility of mitigating undesirable human impacts on stream and riparian ecosystems through the design of efficient and representative assessment and monitoring programs (Montgomery and Buffington 1997, Montgomery and MacDonald 2002).

Stream channel classification systems use similarities of form and/or process to discretely organize complex landscape features that display both relatively continuous longitudinal variation (Vannote et al. 1980) and sharp, local discontinuities (Montgomery 1999, Benda et al. 2004). A number of stream classification schemes have been developed (Schumm, 1981 Rosgen 1996). Successful geomorphic classification systems are process-based, applicable across a range of spatial and temporal scales, and capable of assessing probable channel responses to a range of natural and anthropogenic disturbances (Naiman et al. 1992). A process-based classification could be employed by SOPN to determine the sensitivity, or resistance and resilience, of park streams to anthropogenic stressors of concern to park managers, and thus provide a basis for objectively prioritizing and selecting sites for monitoring (Frissel et al.1986).

Table 2. Stresses and impacts on streamflow regime

Stresses	Effects	Indicators
Surface Water Diversions (△ Streamflow)	↓ Streamflow, Stream Velocities, Depth of Water	Stream Stage / Discharge
Groundwater Pumping (△ Baseflow, Streamflow)	↓ Baseflow, Streamflow, Stream Velocities, Depth of Water	Groundwater Level, Stream Stage / Discharge (Baseflow)
△ Local Stream Base Level(s)	↓ or ↑ Stream Velocities	Local Stream Velocities, Stage
Impoundments	↓ Stream Velocities, Temporal Variations in Streamflow, ↑ Depth of Water	Stream Stage / Discharge (Regulated Dams)
Bridges, Ramps, Docks (instream structures)	↓ and ↑ Stream Velocities, Depth of Water	Local Stream Velocities, Depth Profile
Bank Stabilization / Channel Straightening	↓ and ↑ Stream Velocities, Depth of Water	Local Stream Velocities, Depth Profile
△ Infiltration / Runoff Rates (due to changes in upland or local land use – e.g., urbanization or agricultural development)	↓ or ↑ Baseflow, Streamflow, Stream Velocities, Depth of Water	Groundwater Level, Stream Stage / Discharge
Tamarisk & Other Phreatophytes	↑ Evapotranspiration, ↓ Streamflow, Stream Velocities, Depth of Water	Stream Stage / Discharge
Clearing of Emergent Vegetation & Woody Debris	↑ Stream Velocities	Local Stream Velocities

Removal of Upland Riparian Vegetation	↓ Energy Dissipation at High Flows	Local Stream Velocities (High Flows)
Flood	↑ Streamflow, Stream Velocities, Depth of Water	Stream Stage / Discharge
Drought	↓ Streamflow, Stream Velocities, Depth of Water	Stream Stage / Discharge
Climate Change (temperature, precipitation, wind)	↓ or ↑ Evapotranspiration, Baseflow, Streamflow, Stream Velocities, Depth of Water	Groundwater Level, Stream Stage / Discharge
Motorized Boating	↑ Local Stream Velocities	Local Stream Velocities

Table 3. Stresses and impacts on stream sediments / geomorphology

Stresses	Effects	Indicators
Surface Water Diversions (△ Streamflow)	↓ Streamflow, △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Bed Composition	Stream Geomorphic Parameters*1
Groundwater Pumping (△ Baseflow, Streamflow)	↓ Baseflow / Streamflow, △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Bed Composition	Stream Geomorphic Parameters*1
△ Local Stream Base Level(s)	△ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Bed Composition	Stream Geomorphic Parameters*1
Impoundments	△ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Bed Composition	Stream Geomorphic Parameters*1
Bridges, Ramps, Docks (instream structures)	△ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Bed Composition	Stream Geomorphic Parameters*1
Shoreline Development (buildings & other structures)	Bank Modification, △ Stream Cross-Sectional Geometry, Entrenchment	Stream Geomorphic Parameters*1
Bank Stabilization / Channel Straightening	△ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Bed Composition	Stream Geomorphic Parameters*1
Dredging / Filling (Riverine Wetlands)	△ Stream Cross-Sectional Geometry, Entrenchment	Stream Geomorphic Parameters*1

△ Infiltration / Runoff Rates (due to changes in upland or local land use – e.g., urbanization or agricultural development)	△ Baseflow / Streamflow, Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Bed Composition	Stream Geomorphic Parameters*1
△ Sediment Load (due to changes in upland or local land use)	△ Suspended Sediment, Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Bed Composition	Suspended Sediment, Stream Geomorphic Parameters*1
Tamarisk	△ Stream Cross-Sectional Geometry (loss of active channel)	Stream Geomorphic Parameters*1
Other Exotic / Invasive Riparian Vegetation	↓ or ↑ Bank Erosion, Sediment Load with Impacts to Stream Geomorphology	Suspended Sediment, Stream Geomorphic Parameters*1
Clearing of Emergent Vegetation & Woody Debris	△ Stream Cross-Sectional Geometry, Longitudinal Profile	Stream Geomorphic Parameters*1
Removal of Upland Riparian Vegetation	↑ Bank Erosion, Sediment Load with Impacts to Stream Geomorphology	Suspended Sediment, Stream Geomorphic Parameters*1
Flood	Possible △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Bed Composition	Stream Geomorphic Parameters*1
Climate Change (temperature, precipitation, wind)	↓ or ↑ Baseflow / Streamflow, △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Bed Composition	Stream Geomorphic Parameters*1

Ungulate Grazing / Trampling	Trampling of Riparian Vegetation & Banks, ↑ Sediment Load, △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Bed Composition	Suspended Sediment, Stream Geomorphic Parameters*1
Instream Driving / Vehicle Crossing	△ Stream Cross-Sectional Geometry, ↑ Suspended Sediment, Redistribution of Bed Material	Suspended Sediment, Stream Geomorphic Parameters*1
Motorized Boating	↑ Suspended Sediment, Redistribution of Bed Material	Suspended Sediment, Stream Geomorphic Parameters*1
Off-Road Vehicle Use	↑ Erosion, Sediment Load, △ Bed Composition	Suspended Sediment, Stream Geomorphic Parameters*1
Sand & Gravel Mining	↑ Sediment Load, △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Bed Composition,	Suspended Sediment, Stream Geomorphic Parameters*1
Altered Fire Regime	△ Sediment Load, Bed Composition	Suspended Sediment, Bed Composition

*1 Channel cross-section, width/depth, entrenchment, rates of bank erosion and downcutting/aggradation, longitudinal profile, sinuosity, channel pattern, channel location
(migration), and pebble count.

Table 4. Stresses and impacts on stream water quality / chemistry

Stresses	Effects	Indicators
Surface Water Diversions (△ Streamflow)	↑ Concentration of Nutrients, Suspended Sediment, & Other Dissolved and Suspended Constituents, Water Temperature	Basic Water Quality Parameters*1, Nutrients*2, Suspended Sediment
Groundwater Pumping (△ Baseflow, Streamflow)	↑ Concentration of Nutrients, Organic Carbon, & Suspended Solids, Water Temperature, △ Concentration of Other Dissolved & Suspended Constituents	Basic Water Quality Parameters*1, Nutrients*2, Suspended Sediment
Impoundments	↓ and ↑ Suspended Sediment	Suspended Sediment, Turbidity
Shoreline Development (buildings & other structures)	↑ Sediment Load, Water Temperature	Basic Water Quality Parameters*1, Suspended Sediment
Bank Stabilization / Channel Straightening	↓ Sediment Load	Suspended Sediment, Turbidity
Dredging / Filling (Riverine Wetlands)	↑ Suspended Sediment, Mobilization of Sorbed Contaminants, ↓ or ↑ Water Temperature	Basic Water Quality Parameters*1, Suspended Sediment
△ Infiltration / Runoff Rates (due to changes in upland or local land use – e.g., urbanization or agricultural development)	↓ or ↑ Sediment Load, Concentration of Other Dissolved & Suspended Constituents, Water Temperature	Basic Water Quality Parameters*1, Suspended Sediment
△ Sediment Load (due to changes in upland or local land use)	↓ or ↑ Suspended Sediment	Suspended Sediment, Turbidity

Non-Point Nutrient & Organic Releases (upland or local land use)	↑ Nutrients, Organic Carbon, Heavy Metals, Riverine Wetland Eutrophication	Basic Water Quality Parameters*1, Nutrients*2, BOD/COD*3
Permitted Wastewater Discharge to Streams	↑ Nutrients, Organic Carbon, Heavy Metals, Aquatic Microorganisms, Riverine Wetland Eutrophication	Aquatic Microorganisms*4, BOD/COD*3, Nutrients*2
Point Contaminant Releases (contaminated sites)	↑ Synthetic Organic Compounds, Petroleum Hydrocarbons, Heavy Metals, Pesticides, Wastewater Contaminants, and/or Other Toxic Substances (as applicable)	Potential Point Source Contaminants*5, BOD/COD*3
Atmospheric Deposition	↑ Nitrogen and Sulphur Compounds, Mercury & Other Metals, Pesticides (as applicable)	Nutrients*2, pH, Mercury & Other Metals, Pesticides (as applicable)
Tamarisk	↑ Salinity	Salinity
Other Exotic / Invasive Riparian Vegetation	↓ or ↑ Bank Erosion, Sediment Load	Suspended Sediment, Turbidity
Exotic / Invasive Aquatic Vegetation	↓ or ↑ Dissolved Oxygen, △ Nutrient Cycling	Basic Water Quality Parameters*1, Nutrients*2
Removal of Upland Riparian Vegetation	↓ Interception of Overland Flow (Nutrients & Contaminants)	Basic Water Quality Parameters*1, Nutrients*2
Flood	↑ Nutrient Load, Suspended Sediment	Nutrients*2, Suspended Sediment, Turbidity
Drought	↑ Concentration of Nutrients, Suspended Sediment, & Other Dissolved and Suspended Constituents, Water Temperature	Basic Water Quality Parameters*1, Nutrients*2, Suspended Sediment
Climate Change (temperature, precipitation, wind)	↓ or ↑ Water Temperature, Algae, Concentration of Dissolved and Suspended Constituents	Basic Water Quality Parameters*1
Ungulate Grazing / Trampling	↑ Aquatic Microorganisms, Sediment Load, Nutrients, Organic Carbon	Aquatic Microorganisms*4, Suspended Sediment, Turbidity, BOD/COD*3

Swimming / Wading	↑ Aquatic Microorganisms, Suspended Sediment	Aquatic Microorganisms[*4], Suspended Sediment, Turbidity
Instream Driving / Vehicle Crossing	↑ Suspended Sediment, Mobilization of Sorbed Contaminants, Petroleum Hydrocarbons	Suspended Sediment, Turbidity, Petroleum Hydrocarbons
Motorized Boating	↑ Suspended Sediment, Mobilization of Sorbed Contaminants, Petroleum Hydrocarbons	Suspended Sediment, Turbidity, Petroleum Hydrocarbons
Off-Road Vehicle Use	↑ Erosion, Sediment Load	Suspended Sediment, Turbidity
Sand & Gravel Mining	↑ Sediment Load	Suspended Sediment, Turbidity
Altered Fire Regime	↓ or ↑ Sediment Load, Nutrients	Suspended Sediment, Turbidity, Nutrients[*2]

*1 Water temperature, pH, dissolved oxygen, major cations and anions, conductivity, alkalinity, and turbidity.

*2 Nitrogen and phosphorous.

*3 Biological oxygen demand, chemical oxygen demand.

*4 Bacteria, viruses, and protozoa.

*5 Synthetic organic compounds, petroleum hydrocarbons, heavy metals, pesticides, and other toxic substances, as applicable.

Table 5. Stresses and impacts on stream biota

Stresses	Effects	Indicators
Surface Water Diversions (△ Streamflow)	↓ Degree of Submergence, Available Habitat, ↑ Concentrations of Dissolved and Suspended Constituents	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Groundwater Pumping (△ Baseflow, Streamflow)	↓ Baseflow, Degree of Submergence, Available Habitat, ↑ Concentrations of Dissolved and Suspended Constituents	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
△ Local Stream Base Level(s)	△ Habitat with △ Stream Geomorphology	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Impoundments	Impede or Reduce Fish Passage	Composition, Abundance, & Distribution of Fish
Bridges, Ramps, Docks (instream structures)	△ Habitat with △ Stream Geomorphology	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Shoreline Development (buildings & other structures)	△ Near-Shore Habitat, Near-Shore Water Quality	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Bank Stabilization / Channel Straightening	Loss of Riparian Vegetation, Bank Habitat	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Dredging / Filling (Riverine Wetlands)	△ Riverine Wetland Habitat, Water Quality	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna

△ Infiltration / Runoff Rates (due to changes in upland or local land use – e.g., urbanization or agricultural development)	△ Streamflow, Stream Geomorphology, Habitat, Water Quality	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
△ Sediment Load (due to changes in upland or local land use)	△ Bed Composition, ↓ or ↑ Areal Extent of Aquatic / Riverine Wetland Habitat	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Non-Point Nutrient & Organic Releases (upland or local land use)	↑ Nutrients, Organic Carbon, Heavy Metals, Riverine Wetland Eutrophication	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Algae
Permitted Wastewater Discharge to Streams	↑ Nutrients, Organic Carbon, Heavy Metals, Riverine Wetland Eutrophication	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Algae
Point Contaminant Releases (contaminated sites)	↑ Synthetic Organic Compounds, Petroleum Hydrocarbons, Heavy Metals, Pesticides, Wastewater Contaminants, and/or Other Toxic Substances (as applicable)	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Atmospheric Deposition	↑ Nitrogen & Sulphur Compounds, pH, Mercury & Other Metals, Pesticides (as applicable)	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Tamarisk & Other Phreatophytes	↑ Salinity, ↓ Depth of Water, Areal Extent of Active Channel / Riverine Wetlands	Tamarisk Abundance & Distribution; Composition, Abundance, & Distribution of Native Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, & Herptofauna

Other Exotic / Invasive Riparian Vegetation	Competition with Noninvasive Native Riparian Vegetation	Composition, Abundance, & Distribution of Riverine Wetland Vegetation
Exotic / Invasive Aquatic Vegetation	Competition with Noninvasive Native Aquatic Vegetation, △ Available Habitat	Composition, Abundance, & Distribution of Aquatic Vegetation, Macroinvertebrates, Fish, & Herptofauna
Clearing of Emergent Vegetation & Woody Debris	Loss of Habitat	Composition, Abundance, & Distribution of Aquatic Vegetation, Macroinvertebrates, Fish, & Herptofauna
Removal of Upland Riparian Vegetation	↓ Cover, △ Habitat	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Exotic / Invasive Periphyton, Fish, or Herptofauna	Competition with Noninvasive Native Periphyton, Fish, and Herptofauna; △ Nutrient Cycling, Dissolved Oxygen	Composition, Abundance, & Distribution of Macroinvertebrates, Fish, & Herptofauna
Flood	△ Habitat with △ Stream Geomorphology, △ Water Quality	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Drought	△ Water Quality	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Climate Change (temperature, precipitation, wind)	↓ or ↑ Air & Water Temperatures, Depth of Water, Concentrations of Dissolved and Suspended Constituents, Riverine Wetland Eutrophication	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Algae
Stream Fragmentation	Loss of Patch Connectivity	Composition, Abundance, & Distribution of Macroinvertebrates, Fish, & Herptofauna
Ungulate Grazing / Trampling	Trampling of Aquatic / Riverine Wetland Vegetation & Banks, ↑ Nutrients, Organic Carbon, Possible Riverine Wetland Eutrophication	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna

Swimming / Wading	Trampling of Aquatic / Riverine Wetland Vegetation, Disruption of Habitat, ↑ Suspended Sediment	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Instream Driving / Vehicle Crossing	Damage to Aquatic / Riverine Wetland Vegetation, Disruption of Habitat, ↑ Suspended Sediment	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Motorized Boating	Disruption of Habitat, ↑ Suspended Sediment, Mobilization of Sorbed Contaminants, Petroleum Hydrocarbons	Composition, Abundance, & Distribution of Aquatic Vegetation, Macroinvertebrates, Fish, & Herptofauna
Off-Road Vehicle Use	↑ Erosion, Suspended Sediment	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Sand & Gravel Mining	Loss of Aquatic / Riverine Wetland Vegetation & Other Habitat, ↑ Sediment Load	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Altered Fire Regime	↑ Sediment Load, Nutrients	Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna

Table 6. Summary of stresses and indicators of stream ecosystem function and condition

Stresses	Indicators
Surface Water Diversions (△ Streamflow)	Stream Stage / Discharge; Stream Geomorphic Parameters[*1]; Basic Water Quality Parameters[*2], Nutrients[*3]; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Groundwater Pumping (△ Baseflow, Streamflow)	Groundwater Level, Stream Stage / Discharge (Baseflow); Stream Geomorphic Parameters[*1]; Basic Water Quality Parameters[*2], Nutrients[*3]; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
△ Local Stream Base Level(s)	Local Stream Velocities, Stage; Stream Geomorphic Parameters[*1]; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Impoundments	Stream Stage / Discharge (Regulated Dams); Stream Geomorphic Parameters[*1]; Suspended Sediment, Turbidity; Composition, Abundance, & Distribution of Fish (Fish Passage)
Bridges, Ramps, Docks (instream structures)	Local Stream Velocities; Stream Geomorphic Parameters[*1]; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Shoreline Development (buildings & other structures)	Stream Geomorphic Parameters[*1]; Basic Water Quality Parameters[*1], Suspended Sediment; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Bank Stabilization / Channel Straightening	Local Stream Velocities; Stream Geomorphic Parameters[*1]; Suspended Sediment, Turbidity; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Dredging / Filling (Riverine Wetlands)	Stream Geomorphic Parameters[*1]; Basic Water Quality Parameters[*1], Suspended Sediment; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna

△ Infiltration / Runoff Rates (due to changes in upland or local land use – e.g., urbanization or agricultural development)	Groundwater Level, Stream Stage / Discharge; Stream Geomorphic Parameters*1; Basic Water Quality Parameters*2, Nutrients*3, Suspended Sediment; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
△ Sediment Load (due to changes in upland or local land use)	Suspended Sediment, Turbidity; Stream Geomorphic Parameters*1; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Non-Point Nutrient & Organic Releases (upland or local land use)	Basic Water Quality Parameters*2, Nutrients*3, BOD/COD*4; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Algae
Permitted Wastewater Discharge to Streams	Aquatic Microorganisms*5, BOD/COD*4, Nutrients*3; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Algae
Point Contaminant Releases (contaminated sites)	Potential Point Source Contaminants*6, BOD/COD*4; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Atmospheric Deposition	Nutrients*3, pH, Mercury & Other Metals, Pesticides (as applicable); Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Tamarisk	Stream Stage / Discharge; Stream Geomorphic Parameters*1; Salinity; Tamarisk Abundance & Distribution; Composition, Abundance, & Distribution of Native Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, & Herptofauna
Other Exotic / Invasive Riparian Vegetation	Suspended Sediment, Turbidity, Stream Geomorphic Parameters*1; Composition, Abundance, & Distribution of Riverine Wetland Vegetation
Exotic / Invasive Aquatic Vegetation	Basic Water Quality Parameters*2, Nutrients*3; Composition, Abundance, & Distribution of Aquatic Vegetation, Macroinvertebrates, Fish, & Herptofauna

Clearing of Emergent Vegetation & Woody Debris	Local Stream Velocities; Stream Geomorphic Parameters*1; Composition, Abundance, & Distribution of Aquatic Vegetation, Macroinvertebrates, Fish, & Herptofauna
Removal of Upland Riparian Vegetation	Local Stream Velocities (High Flows); Stream Geomorphic Parameters*1; Suspended Sediment; Basic Water Quality Parameters*2, Nutrients*3; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Exotic / Invasive Periphyton, Fish, & Herptofauna	Composition, Abundance, & Distribution of Macroinvertebrates, Fish, & Herptofauna
Flood	Stream Stage / Discharge; Stream Geomorphic Parameters*1; Basic Water Quality Parameters*2, Nutrients*3, Suspended Sediment; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Drought	Stream Stage / Discharge; Basic Water Quality Parameters*2, Nutrients*3, Suspended Sediment; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Climate Change (temperature, precipitation, wind)	Groundwater Level, Stream Stage / Discharge; Stream Geomorphic Parameters*1; Basic Water Quality Parameters*2; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Algae
Stream Fragmentation	Composition, Abundance, & Distribution of Macroinvertebrates, Fish, & Herptofauna
Ungulate Grazing / Trampling	Suspended Sediment, Stream Geomorphic Parameters*1; Aquatic Microorganisms*5, Suspended Sediment, Turbidity, BOD/COD*4; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Swimming / Wading	Aquatic Microorganisms*5, Suspended Sediment, Turbidity; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Instream Driving / Vehicle Crossing	Suspended Sediment, Turbidity, Petroleum Hydrocarbons; Stream Geomorphic Parameters*1; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna

Motorized Boating	Local Stream Velocities; Suspended Sediment, Turbidity, Petroleum Hydrocarbons; Stream Geomorphic Parameters[*1]; Composition, Abundance, & Distribution of Aquatic Vegetation, Macroinvertebrates, Fish, & Herptofauna
Off-Road Vehicle Use	Suspended Sediment, Suspended Sediment, Turbidity; Stream Geomorphic Parameters[*1]; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Sand & Gravel Mining	Suspended Sediment, Suspended Sediment, Turbidity; Stream Geomorphic Parameters[*1]; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Altered Fire Regime	Suspended Sediment, Turbidity, Nutrients[*3]; Bed Composition; Composition, Abundance, & Distribution of Aquatic / Riverine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna

*1 Channel cross-section, width/depth, entrenchment, rates of bank erosion and downcutting/aggradation, longitudinal profile, sinuosity, channel pattern, channel location (migration), and pebble count.

*2 Water temperature, pH, dissolved oxygen, major cations and anions, conductivity, alkalinity, and turbidity.

*3 Nitrogen and phosphorous.

*4 Biological oxygen demand, chemical oxygen demand.

*5 Bacteria, viruses, and protozoa.

*6 Synthetic organic compounds, petroleum hydrocarbons, heavy metals, pesticides, and other toxic substances, as applicable.

W.3. RESERVOIR ECOSYSTEM MODEL

Reservoirs at Lake Meredith NRA and Chickasaw NRA (Lake Meredith, Lake of the Arbuckles, and Veterans Lake) are man-made lakes, managed by the National Park Service as recreational resources and operated as public drinking water supplies by other entities. The Pedernales River in the vicinity of Lyndon B. Johnson NHP has three small dams on it and the river there has components of both a riverine and lacustrine system.

W.3.1. Summary of Drivers, Stressors, Attributes, and Indicators of Reservoir Ecosystem Function and Condition

Man-made structures (e.g., diversions, dams, and spillways), as well as natural conditions such as climate, atmospheric conditions, geology, landform, time, and upland watershed conditions, are drivers (major forces of change) for Lake Meredith, Lake of the Arbuckles, and Veterans Lake ecosystems (Figure 11).

W.3.2. Reservoir Ecosystem Function under Desired Conditions

Reservoirs are human-engineered habitats and relatively young compared to many ecological processes. Little is known about the dynamics of aquatic organisms and nutrient and mineral cycling in reservoirs, although basic principles of lake ecology are presumed to apply. Habitats of reservoir ecosystems (the pelagial, littoral, and profundal zones), 'resources' influencing the function of reservoir ecosystems (Chapin et al. 1996), are described in this section. The attributes and functioning of SOPN reservoir ecosystems under 'desired' conditions is summarized in Figure 12.

Lakes (reservoirs) are highly valued for the recreational opportunities and esthetic experiences they provide. They have also attracted scientists for ecosystem studies because of their diversity, relative ease of isolating specific subunits, the ability to conduct ecosystem-level manipulations, and more recently to use lakes for documenting changes in the global environment (Davis 1981). Because they are sensitive to inputs from watershed and air sheds, lake ecosystems in most areas of the world are likely to have experienced at least some level of human-induced, ecological change.

This model is intentionally general in order to describe a range of potential conditions at Lake Meredith, Lake of the Arbuckles, and Veterans Lake, including:

Trophic status (oligotrophic, eutrophic, dystrophic…)

Annual mixing pattern (dimictic, polymictic, meromictic)

Morphometry (mean depth – volume/area, maximum depth, shoreline development, mean slope…)

Water Source (stream inflows and outflows, groundwater seepage to and from the reservoir…)

Additionally, responses of reservoir ecosystems may vary considerably in duration depending on the subsystem affected. Frost et al. (1988) emphasize the importance of recognizing variations in scale in studying and understanding lake ecosystems. Hence reservoirs (lakes) may show responses on evolutionary time scales (e.g. predator-prey associations) (DeAngelis et al. 1985) to time scales of seconds (phosphorus cycling) (Norman and Sager 1978). On intermediate scales, the introduction of an exotic crayfish has been shown to alter the littoral community for several years (Lodge and Lorman 1987).

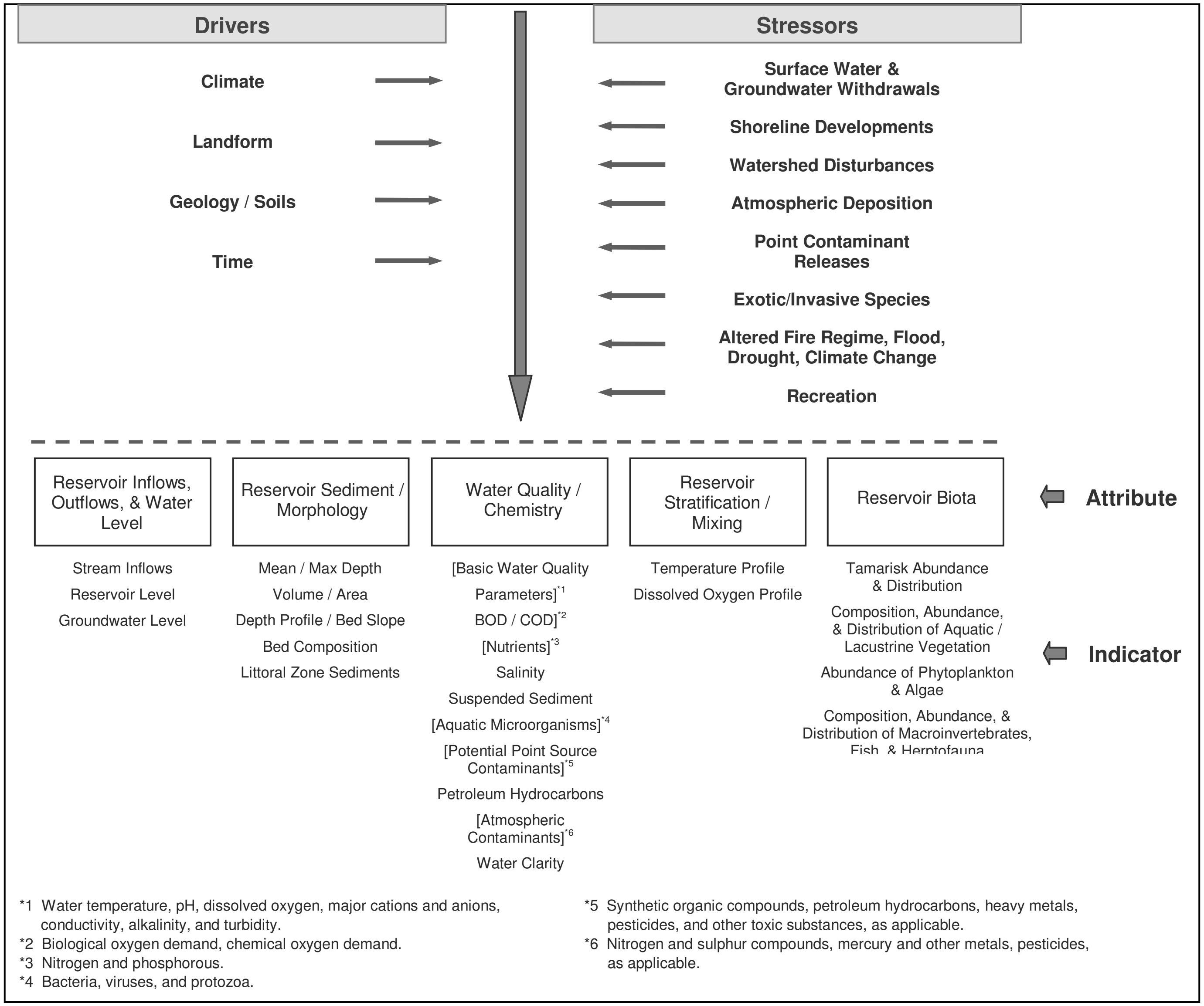


Figure 11. Overview of drivers, stressors, attributes, and indicators of reservoir ecosystem function and condition.

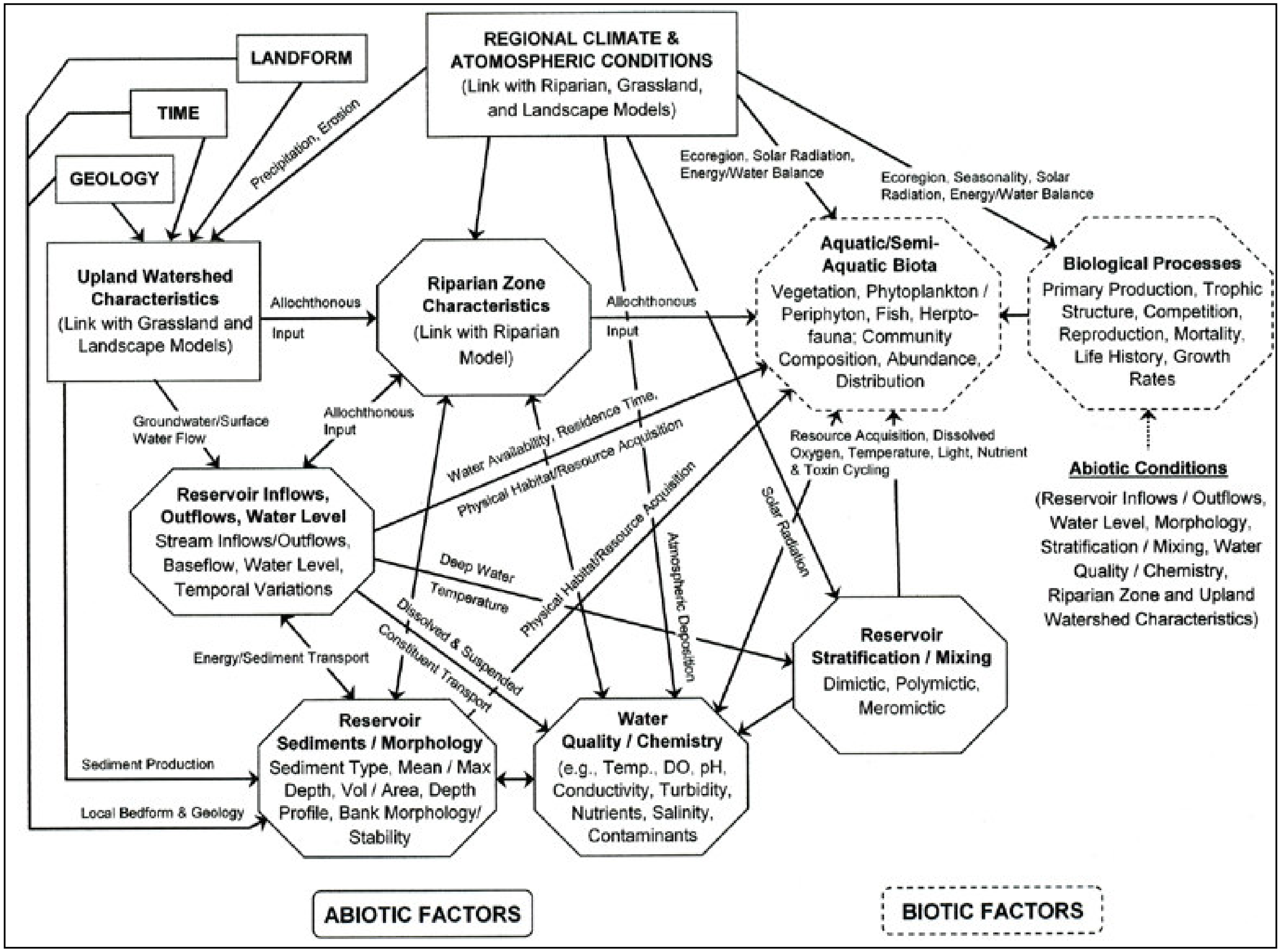


Figure 12. Desired reservoir ecosystem function.

W.3.2.1. Major Habitats of Reservoir Ecosystems

The *pelagial zone* has long been the focus of lake ecology studies. This open water habitat supports the plankton community, the phytoplankton and zooplankton, as well as the ichthyoplankton. The phytoplankton are dependent on water motion for maintaining their position in the water column in addition to various adaptation in morphology of the cells to increase their surface area. Hence the phytoplankton will generally be distributed in the pelagial zone to the depth of mixing in the reservoir (in shallow reservoirs to the bottom, in stratified reservoirs to the thermocline) but functionally their effective distribution is a function of light, specifically the attenuation of light with depth. Phytoplankton photosynthesis is considered to prevail to that depth where about 1 percent of surface light remains, known as the compensation depth. Beyond this depth, respiration and decomposition processes exceed any contribution from photosynthesis.

In certain stratified reservoirs of sufficient clarity, the compensation depth may extend below the mixing depth into or below the thermocline. Photosynthetic production of oxygen can then help to create a habitat for cold water fishes in this layer, complementing the warm water habitat of the upper epilimnion. In other reservoirs, the compensation depth can be shallower than the mixing depth producing a light limiting condition for production. The zooplankton, because of their mobility, typically show variations in vertical distribution in a reservoir due to vertical migration in response to diurnal changes in light intensity in the water column. Factors influencing the underwater light regime are thus of considerable ecological importance in the ecosystem.

The *littoral zone* (lacustrine wetlands) has been recognized as a major component of lake ecosystems in recent decades. Wetzel (1979) showed the important role of detritus originating in submersed aquatic vegetation (SAV) of the littoral zone on the overall metabolism of a lake (reservoir). Carpenter and Lodge (1986) stressed the important interactions of the littoral community - between sediment and water and between shoreline and open water. The major producers in this community, SAV, provide habitat and food for fishes, muskrats, waterfowl amphibians and invertebrates. Additionally, algal periphyton can be important contributors to littoral production in certain reservoirs. The littoral zone includes a major nutrient pool that cycles slowly compared to the pelagial zone. It influences water temperature in shallow waters, reduces water movement, and through self-shading increases light attenuation. Cole (1994) notes that the littoral community often has the highest biodiversity and biological production in a lake (reservoir) ecosystem.

The aerial extent of development of the littoral community is a function of the substrate, nutrient levels, and bottom slope of the nearshore environment. The depth distribution is a function of light attenuation and ultimately pressure, at least for angiosperm SAV. Hence factors decreasing light availability play a major role in the degradation of this community (Sager et al. 1996). Nutrients are also important for the growth of the SAV that reach their maximum growth and biomass at roughly intermediate conditions between oligotrophic and eutrophic status (Wetzel 1979). Nutrient limitation in sediments and water seems to be in effect in oligotrophic reservoirs, while the light shading effect of increased phytoplankton biomass can limit depth distribution and growth in eutrophic reservoirs (Wetzel 1983).

The *profundal zone* includes the deep water, bottom sediment environment typically found in stratified lakes (reservoirs) where it is dark and cold. Habitat diversity is low. Processes of organic matter sedimentation and decomposition produce a physically uniform texture in bottom sediments, though the qualitative composition includes a range of inorganic and organic substances. In eutrophic reservoirs, the hypolimnetic water and sediments will have varying degrees of oxygen depletion while in oligotrophic reservoirs, oxygen depletion is minimal in the hypolimnion, though oxygen depletion can occur in the pore water of the organically richer sediments.

In unstratified reservoirs of moderate depth, light may not reach the profundal sediments, but with full mixing of the water column, bottom temperatures and oxygen levels will be comparable to the surface waters. Higher water temperatures, consequently, can have a positive effect on metabolism and growth on the benthos in such reservoirs. In shallow reservoirs, the littoral zone may prevail throughout the basin and a profundal zone is lacking. Maximum depth and trophic status thus are important influences on the development of sediment habitat among reservoirs.

In eutrophic reservoirs, the profundal benthos adapt in various ways to the oxygen stress and generally include at least a few macroinvertebrates. In oligotrophic reservoirs the fauna associated with the profundal habitat is generally more diverse, even though biomass and production may be lower than in eutrophic reservoirs. The profundal zone in oligotrophic reservoirs may include some of the same taxa found in eutrophic reservoirs, in addition to other species.

W.3.2.2. Natural Processes

Hutchinson (1969) used the phrase “trophic equilibrium” to describe the close linkage between a lake (reservoir) and its watershed. The linkage is based on the geological character of the watershed, the fertility of the soil and bedrock, and the trophic status of the reservoir that, through transport, receives nutrients from the watershed. In the natural state and over the long term, this linkage would achieve an equilibrium condition. Major events such as extreme precipitation and runoff, fire, and erosion, foster increases in nutrient loading or hydrological washout, leading to changes in the reservoir of varying duration. Reservoirs are quite sensitive to events and process external to their basins. Features of the reservoir itself, such as basin morphometry, water clarity, and food chain structure, interact with external influences to produce reservoir ecosystem features.

W.3.3. Natural and Anthropogenic Stresses and Reservoir Ecosystem Response

Significant changes in any of the four interactive controls – climate, resource supply, major biotic functional groups, or disturbance regime (Chapin et al. 1996) – are predicted to result in a new ecosystem with different characteristics than the original system. This section describes predominant anthropogenic disturbance regimes and specific stressors and responses of reservoir ecosystems at Lake Meredith NRA and Chickasaw NRA.

W.3.3.1. Anthropogenic Influences

Watershed Disturbances - Watershed disturbances such as agriculture, urban development, logging and fire are major influences on reservoir ecosystems (Scrimgeour et al. 2001, Garrison and Wakeman 2000). Loss of protective vegetative cover on soil leads to increased loading of nutrients and sediments over the natural loads which stimulate increased growth of phytoplankton and submersed aquatic vegetation (SAV). These eutrophication processes can lead to excessive growth of nuisance algae, loss of SAV in the littoral community due to increased light attenuation, and altered food chain processes and efficiencies owing to less palatable phytoplankton species (Richman and Dodson 1983, Sager and Richman 1991, Kemp et al. 2001)

Shoreline Disturbances - Shoreline disturbances such as clearing emergent and submersed vegetation and removing woody debris to create swimming areas can lead to a loss of aquatic habitat, decreased amphibian populations (Woodford and Meyer 2003), reduction in fish growth rates (Schindler et al. 2000), and decreased water quality (Garrison and Wakeman 2000).

Atmospheric Deposition - Atmospheric deposition of contaminants illustrates the broad extent to which external factors affect reservoir ecosystems. The watershed area for a given reservoir is, in most cases, small in comparison to the air shed. Substances can be transported great distances through the atmosphere before falling on the reservoir or upstream tributaries. Mercury is a problem in water bodies throughout the United States. Following deposition in the reservoir, inorganic mercury undergoes a transformation to methyl mercury, the form in which it bioaccumulates in the food chain. Animals, including humans and wildlife (such as loons and eagles) that eat contaminated fish, are susceptible to central nervous system damage. The affect of mercury on human fetuses and newborn infants is of prime concern (ATSDR 1999). In the 1990s, certain regions experienced a decline in mercury deposition rates that was followed by gradual declines in lake water and fish (Watras et al. 2000).

Deposition of sulfur and nitrogen oxides produced by combustion of fossil fuels (coal-fired power plants, automobiles and other fuel burning processes) causes acidification of lakes (reservoirs). Atmospheric transport of sulfur and nitrogen oxides may occur over great distances, as well as nearby sources. Not all lakes respond equally. The buffering capacity of lakes (reservoirs) is determined by the geological setting. Other factors, such as watershed gradient, vegetative cover, and food web structure, play a role in reservoir response.

Acidification of lakes (reservoirs) by atmospheric deposition has broad ranging ecological affects, in addition to its influence on the methylization of mercury. The Clean Air Act Amendment of 1990 called for a decrease in sulfur dioxide emissions. Some acidified lakes are now showing recovery, others are not.

Recreation - Recreation activities are increasingly regarded as a major influence on lake (reservoir) ecosystems. Considerable pressure from fishing and boating can lead to impacts on the age and size structure of fish populations and the food web (Reed-Andersen et al. 2000a; Landres et al. 2001, Harig and Bain 1998). Exotic and invasive species can result from transporting boats from lake to lake, inadvertently carrying entangled plant material and associated biota (Johnson 2001) such as zebra mussels (*Dreissena polymorpha*) (Kraft et al. 2002, Reed-Andersen et al. 2000b, Engel 1990). Similarly, exotic/invasive organisms are sometimes carried as bait for fishing and subsequently released (Lodge and Lorman 1987, WASAL 2003). In most cases, successful invasive species have impacts similar to exotic species - elimination of native species through predation and/or competition, alteration of habitats, and modification of food webs.

Climate Change - Climate Change could become one of the most serious anthropogenic influences on ecosystems of all types. In an increasing number of scenarios and predictions being reported concerning the effects of climate change on reservoirs, nearly all communities and processes show some response via effects of altered temperature regimes, the alteration of hydrologic patterns, and interactions with numerous other stressors. Geographic location may be an important determinant of temperature response.

W.3.3.2. Specific Stressors

Nutrient Loading - Inputs to lakes (reservoirs) of the key nutrients nitrogen, and especially phosphorus, are generally considered major influences on lake ecosystems. The lake (reservoir) response to changes in nutrient inputs is often fast, consisting of a pulse in growth of the primary producers, especially phytoplankton. Algal turnover rates are typically high, and the uptake and turnover rate of phosphorus by algae is even faster (Norman and Sager 1978). Movement of this growth pulse through the food chain is much slower for organisms higher in the food chain. A sustained increase in nutrient loading will ultimately have some effect in the higher trophic levels. Anthropogenic disturbances in the watershed can increase nutrient loading, most of which is originate as non-point sources (Bennett et al. 1999, Klump et al. 1996, Carpenter et al. 1998). Eutrophication leads to changes in phytoplankton species composition, size structure, and growth rates, all of which have relevance to the pelagial food web. The increase in algal biomass affects water clarity and the depth distribution of photosynthesis. The depth distribution, and subsequently the aerial extent of the littoral community, are generally reduced as well. Other effects of eutrophication include impairment of esthetics and recreational values, loss of deep-water habitats, and hypolimnetic oxygen depletion.

Sediment Loading - The loading of suspended sediments and detritus from the watershed is a function of soil temperature, moisture, hydrology, and watershed morphology (Dillon and Molot 1997). In the absence of anthropogenic influences sediment loading may vary considerably, increasing as a function of natural catastrophes such as fire and floods and herbivory, which enhance soil erosion. Due to urban development, agriculture, logging, fire and other anthropogenic activities, the watershed generally discharges an increased load of sediment and detritus to the lake (reservoir). The impacts of increased levels of suspended solids include increased light extinction, exacerbating the effects of increased nutrient loading on the penetration of light due to increased algal populations (Millard and Sager 1994).

Metals/Toxic Loading - Mercury contamination in lake (reservoir) ecosystems experiencing aerial deposition can be found in most organisms and habitats of lakes (Boening 2000, Mackay and Toose 2003). In fish, mercury concentrations vary directly with size and age, indicating bioaccumulation through the food web (Glass 2001). As a result, fish of standard size at the top of the food chain (apex predators) are used for comparison purposes in assessing mercury contamination in lakes (Kallemeyn et al. 2003). Effects of mercury contamination may extended from thelake (reservoir) ecosystem through fish-eating birds such as eagles, osprey (*Pandion haliaetus*) and loons (*Gavia spp.*), and a range of mammals, including humans (Mackay and Toose 2003).

Physiological effects of mercury relate to the fact that it accumulates in nervous system tissue. In humans, mercury exposure in pregnant women can lead to neurodevelopment effects in fetuses and children (Vahter et al. 2002). Consumption of contaminated game fish must therefore be closely controlled. In birds and other wildlife, physiological effects are difficult to ascertain in the field because of interacting effects of food, predation and the presence of other types of contaminants (Karasov and Meyer 2000). In general, Boening (2000) notes that fish exposed to sublethal concentrations show a variety of physiological and reproductive abnormalities and that birds fed inorganic mercury showed a reduction in food intake and poor growth. Boening (2000) also states that the form of mercury retained in birds depends on the species, location, and target organ.

Indicators of critical mercury concentrations have been recommended. Scheuhammer and Bond (1991) suggest feather concentrations of 20ug/g as a toxic effect threshold. Barr (1986) reported impaired loon reproduction when mercury residues in forage fish exceeded 0.3ug/g. Atmospheric deposition can also be a significant source of organochlorine compounds (PCBs and PBDEs) and other contaminants to lakes (reservoirs). Lake Meredith is included on the 303(d) list of impaired water bodies in connection with mercury contamination identfied in fish tissues.

Acid Deposition - Sulfur and nitrogen oxides discharged to the atmosphere react with water vapor to form sulfuric and nitric acids that are deposited on the earth as acid rain, snow, or fog. Effects on lake (reservoir) ecosystems depend on the buffering or acid neutralizing capacity (ANC) of the lake. Soft water lakes of low ANC (< 100 mueq/L) (Stoddard et al. 1998) have experienced declines in diversity of flora and fauna through reproductive failure or direct mortality. The Clean Air Act of 1970 and Amendment of 1990 were followed by emission reductions in North America and Europe that resulted in decreased sulfur depositions of up to 50 percent (Skjelkvale et al. 2001). On a broad scale, Skjelkvale et al. (2001) observed downward trends in lake sulfate concentrations from 1989-1998 in all regions of the United States, with low ANC sites showing the highest rates of recovery.

Exotic Species - Exotic, invasive species may be characterized by elevated fecundity, rapid growth and early maturity - typical traits of r-selected species where physiological tolerance is not a requirement for success (McMahon 2000). Their impact on lake (reservoir) ecosystems is one of a trend towards homogenization of flora and fauna through direct processes of competition for food and space, predation and grazing, and alterations of food web structure (Rahel 2002).

Prevention seems to be the only effective solution. Once established, most are extremely difficult to remove.

Fishing and Boating - Aquatic resources of the national parks generally receive considerable recreational pressure from visitors. Lakes and streams are prized for their remoteness and esthetics, but subjected to a range of stresses, largely from fishing and boating. Fish stocking of native and non-native species to meet public demand may compromise some ecological values of SOPN reservoirs (Landres et al. 2001).

Temperature and Precipitation Changes - It is beyond the scope of this report to review the full spectrum of scenarios and predictions offered in relation to lake (reservoir) ecosystem responses to climate change. Some may wonder how managers can deal with this global phenomenon. Yet awareness of expected effects of climate change may be important when interpreting observations of changes in reservoir ecosystem features. General scenarios include change towards warmer and drier climates in the century ahead (Davis et al. 2000). Translating this generalization into specific effects is not easy given the complex interactions of acidification, climate warming, and increased ultraviolet light exposure as a result of stratospheric ozone depletion (e.g., Schindler 1999).

Magnuson et al. (2000) noted a recent trend toward shorter periods of ice cover in lakes and rivers of the northern hemisphere. If so, lakes (reservoirs) will be subject to higher surface water temperatures at earlier times in the spring and later in the fall. The potential effects are many, including changes in the timing of events such as fish spawning and hatching in relation to plankton (food source) availability, the extent of oxygen depletion (during periods of extended summer stratification), effects on cold-water habitats/fish, and warm water species with limited ability to acclimate to higher temperatures.

Planning for ecosystem change may be the best strategy (e.g., WASAL 2003, Magnuson et al. in press).

Stresses and impacts on reservoir inflows/outflows and reservoir levels, reservoir sediments/ morphology, water quality/chemistry (including palustrine wetlands), reservoir stratification/mixing, and reservoir biota are enumerated in Tables 7 through 11, respectively, accompaned by indicators of ecosystem response/condition. For each major stressor identified, indicators of ecosystem condition are summarized in Table 12.

Table 7. Stresses and impacts on reservoir inflows, outflows, and water level

Stresses	Effects	Indicators
Surface Water Diversions (from reservoir or upstream tributaries)	↓ Streamflow (Upstream Tributaries) or Direct Lowering of Reservoir Level	Stream Discharge (Upstream Tributaries), Reservoir Level
Groundwater Pumping	↓ Baseflow to Reservoir & Upstream Tributaries, Streamflow (Upstream Tributaries), Reservoir Level	Groundwater Level, Stream Discharge (Baseflow to Upstream Tributaries), Reservoir Level
Shoreline Development (buildings & other structures)	↑ Overland Flow, Reservoir Level	Reservoir Level
△ Infiltration / Runoff Rates (due to changes in upland or local land use – e.g., urbanization or agricultural development)	↓ or ↑ Baseflow to Reservoir & Upstream Tributaries, Streamflow (Runoff), Reservoir Level	Stream Discharge (Upstream Tributaries), Reservoir Level
Tamarisk & Other Phreatophytes	↑ Evapotranspiration, ↓ Reservoir Level	Reservoir Level
Flood	↑ Streamflow (Upstream Tributaries), Reservoir Level	Stream Discharge (Upstream Tributaries), Reservoir Level
Drought	↑ Evaporation / Evapotranspiration, ↓ Streamflow (Upstream Tributaries), Reservoir Level	Stream Discharge (Upstream Tributaries), Reservoir Level
Climate Change (temperature, precipitation, wind)	↓ or ↑ Evaporation / Evapotranspiration, Baseflow to Reservoir & Upstream Tributaries, Streamflow (Upstream Tributaries), Reservoir Level	Groundwater Level, Stream Discharge (Baseflow to Upstream Tributaries), Reservoir Level

Table 8. Stresses and impacts on reservoir sediments / morphology

Stresses	Effects	Indicators
Shoreline Development (buildings & other structures)	Bank Modification	Bed Composition, Reservoir Morphometry*1
Bank Stabilization / Channel Straightening	△ Bank Morphology / Sediments	Bed Composition, Reservoir Morphometry*1
Bank Instability	△ Bank Morphology	Reservoir Morphometry*1
Dredging / Filling (Lacustrine Wetlands)	△ Wetland Morphology	Reservoir Morphometry*1
△ Sediment Load (due to changes in upland or local land use)	↓ or ↑ Deposition, △ Reservoir Morphology / Bed Composition	Bed Composition, Reservoir Morphometry*1
Tamarisk & Other Phreatophytes	↑ Evapotranspiration, ↓ Reservoir Level, Areal Extent / Location of Littoral Zone	Reservoir Morphometry *1
Other Exotic / Invasive Riparian Vegetation	↓ or ↑ Bank Erosion, Sediment Load, △ Reservoir Morphology / Bed Composition	Bed Composition, Reservoir Morphometry*1
Removal of Upland Riparian Vegetation	↑ Bank Erosion, Sediment Load, △ Reservoir Morphology / Bed Composition	Bed Composition, Reservoir Morphometry*1
Flooding	↑ Deposition / Scouring	Bed Composition, Reservoir Morphometry*1
Removal of Riparian Vegetation	↑ Bank Erosion, Deposition	Bed Composition (Littoral Zone), Reservoir Morphometry*1
Ungulate Grazing / Trampling	Trampling of Riparian Vegetation & Banks, ↑ Bank Erosion, Deposition	Bed Composition (Littoral Zone), Reservoir Morphometry*1
Off-Road Vehicle Use	↑ Bank Erosion, Sediment Deposition	Bed Composition (Littoral Zone), Reservoir Morphometry*1

Altered Fire Regime	△ Sediment Load / Deposition	Bed Composition, Reservoir Morphometry*1

*1 Reservoir mean/maximum depth, volume/area, depth profile/bed slope.

Table 9. Stresses and impacts on reservoir water quality / chemistry

Stresses	Effects	Indicators
Surface Water Diversions (from reservoir or upstream tributaries)	↑ Concentration of Nutrients, Suspended Sediment, & Other Dissolved and Suspended Constituents, Water Temperature	Nutrients*1, BOD/COD*2, DO Profile*3, Water Clarity, Basic Water Quality Parameters*4, Temperature Profile
Groundwater Pumping	↑ Concentration of Nutrients, Organic Carbon, & Suspended Solids, Water Temperature, △ Concentration of Other Dissolved & Suspended Constituents	Nutrients*1, BOD/COD*2, DO Profile*3, Water Clarity, Basic Water Quality Parameters*4, Temperature Profile
Shoreline Development (buildings & other structures)	↑ Sediment Load, Water Temperature	Suspended Sediment, Water Clarity, Basic Water Quality Parameters*4, Temperature Profile
Bank Stabilization	↓ Sediment Load	Suspended Sediment, Water Clarity
Bank Instability	↑ Sediment Load	Suspended Sediment, Water Clarity
Dredging / Filling (Palustrine Wetlands)	↑ Suspended Sediment, Mobilization of Sorbed Contaminants, ↓ or ↑ Water Temperature / Gradient	Suspended Sediment, Water Clarity, Temperature Profile
△ Infiltration / Runoff Rates (due to changes in upland or local land use – e.g., urbanization or agricultural development)	↓ or ↑ Sediment Load, Concentration of Other Dissolved & Suspended Constituents, Water Temperature	Nutrients*1, BOD/COD*2, DO Profile*3, Water Clarity, Basic Water Quality Parameters*4, Temperature Profile
△ Sediment Load (due to changes in upland or local land use)	↓ or ↑ Suspended Sediment	Suspended Sediment, Water Clarity

Non-Point Nutrient & Organic Releases (upland or local land use)	↑ Nutrient Load, Rate of Organic Carbon Input, Heavy Metals, Eutrophication	Nutrients[*1], BOD/COD[*2], DO Profile[*3], Water Clarity, Basic Water Quality Parameters[*4]
Permitted Wastewater Discharge to Upland Tributaries	↑ Nutrient Load, Rate of Organic Carbon Input, Heavy Metals, Eutrophication, Aquatic Microorganisms	Nutrients[*1], BOD/COD[*2], DO Profile[*3], Water Clarity, Basic Water Quality Parameters[*4], Aquatic Microorganisms[*5]
Point Contaminant Releases (contaminated sites)	↑ Synthetic Organic Compounds, Petroleum Hydrocarbons, Heavy Metals, Pesticides, Wastewater Contaminants, & Other Toxic Substances (as applicable)	Potential Point Source Contaminants[*6], BOD/COD[*2]
Atmospheric Deposition	↑ Nitrogen & Sulphur Compounds, Mercury & Other Metals, Pesticides (as applicable)	Nutrients[*1], pH, Mercury & Other Metals, Pesticides (as applicable)
Tamarisk	↑ Salinity	Salinity
Other Exotic / Invasive Riparian Vegetation	↓ or ↑ Bank Erosion, Sediment Load	Suspended Sediment, Water Clarity
Exotic / Invasive Aquatic Vegetation	↓ or ↑ Dissolved Oxygen, △ Nutrient Cycling	Basic Water Quality Parameters[*4], Nutrients[*1]
Removal of Upland Riparian Vegetation	↓ Interception of Overland Flow (Nutrients, Contaminants, Sediments)	Basic Water Quality Parameters[*4], Nutrients[*1], Suspended Sediment, Water Clarity
Flood	↑ Concentration of Nutrients, Suspended Sediment, & Other Dissolved and Suspended Constituents, ↓ Water Temperature	Nutrients[*1], Suspended Sediment, Water Clarity, Basic Water Quality Parameters[*4]
Drought	↑ Concentration of Nutrients, Suspended Sediment, & Other Dissolved and Suspended Constituents, Water Temperature	Nutrients[*1], Suspended Sediment, Water Clarity, Basic Water Quality Parameters[*4]
Climate Change (temperature, precipitation, wind)	↓ or ↑ Nutrient Load, Suspended Sediment, Concentration of Other Dissolved & Suspended Constituents, Water Temperature	Nutrients[*1], BOD/COD[*2], DO Profile[*3], Water Clarity, Basic Water Quality Parameters[*4], Temperature Profile

Ungulate Grazing / Trampling	↑ Nutrient Loading, Rate of Organic Carbon Input, Aquatic Microorganisms	Nutrients*1, BOD/COD*2, DO Profile*3, Suspended Sediment, Water Clarity, Aquatic Microorganisms*5
Swimming / Wading	↑ Suspended Sediment, Aquatic Microorganisms	Suspended Sediment, Water Clarity, Aquatic Microorganisms*5
Motorized Boating	↑ Suspended Sediment, Mobilization of Sorbed Contaminants, Petroleum Hydrocarbons	Suspended Sediment, Water Clarity, Petroleum Hydrocarbons
Off-Road Vehicle Use	↑ Bank Erosion, Deposition	Suspended Sediment, Water Clarity
Altered Fire Regime	↓ or ↑ Nutrient Load, Rate of Organic Carbon Input, Suspended Sediment	Nutrients*1, BOD/COD*2, DO Profile*3, Water Clarity, Basic Water Quality Parameters*4, Suspended Sediment

*1 Nitrogen and phosphorous.

*2 Biological oxygen demand, chemical oxygen demand.

*3 Dissolve oxygen profile.

*4 Water temperature, pH, dissolved oxygen, major cations and anions, conductivity, alkalinity, and turbidity.

*5 Bacteria, viruses, and protozoa.

*6 Synthetic organic compounds, petroleum hydrocarbons, heavy metals, pesticides, and other toxic substances, as applicable.

Table 10. Stresses and impacts on reservoir stratification / mixing

Stresses	Effects	Indicators
Surface Water Diversions (from reservoir or upstream tributaries)	↑ Water Temperature, △ Water Temperature & Dissolved Oxygen Gradients	Temperature Profile, DO Profile[*1]
Groundwater Pumping	↑ Water Temperature, ↓ Water Temperature Gradient, △ Dissolved Oxygen Gradient	Temperature Profile, DO Profile[*1]
△ Infiltration / Runoff Rates (due to changes in upland or local land use – e.g., urbanization or agricultural development)	↑ Water Temperature, △ Water Temperature & Dissolved Oxygen Gradients	Temperature Profile, DO Profile[*1]
Climate Change (temperature, precipitation, wind)	↓ or ↑ Air & Water Temperatures, △ Water Temperature & Dissolved Oxygen Gradients	Temperature Profile, DO Profile[*1]

*1 Dissolve oxygen profile.

Table 11. Stresses and impacts on reservoir biota

Stresses	Effects	Indicators
Surface Water Diversions (from reservoir or upstream tributaries)	↑ Concentration of Nutrients, Suspended Sediment, & Other Dissolved and Suspended Constituents, Water Temperature, Phytoplankton, Algae, Light Extinction, ↓ Depth Submergence, △ Areal Extent / Location of Littoral Zone	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae
Groundwater Pumping	↑ Concentration of Nutrients, Organic Carbon, Suspended Solids, Water Temperature, Phytoplankton, Algae, Light Extinction, ↓ Depth Submergence, △ Areal Extent / Location of Littoral Zone	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae
Shoreline Development (buildings & other structures)	Loss of Near-Shore Habitat (Bank Modification), ↓ Amphibians, Waterfowl	Composition, Abundance, & Distribution of Littoral Zone Vegetation, Macroinvertebrates, & Herptofauna
Bank Stabilization	Loss of Bank Habitat, ↓ Amphibians, Waterfowl	Composition, Abundance, & Distribution of Littoral Zone Vegetation, Macroinvertebrates, & Herptofauna
Bank Instability	Loss of Bank Habitat, ↓ Amphibians, Waterfowl	Composition, Abundance, & Distribution of Littoral Zone Vegetation, Macroinvertebrates, & Herptofauna
Dredging / Filling (Lacustrine Wetlands)	Loss or Alteration of Lacustrine Wetland Habitat	Composition, Abundance, & Distribution of Littoral Zone Vegetation, Macroinvertebrates, & Herptofauna
△ Infiltration / Runoff Rates (due to changes in upland or local land use – e.g., urbanization or agricultural development)	↑ Nutrient Load, Rate of Organic Carbon Input, Sediment Load, Concentration of Other Dissolved & Suspended Constituents, Water Temperature, Phytoplankton, Algae, Light Extinction	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae

△ Sediment Load (due to changes in upland or local land use)	↓ or ↑ Suspended Sediment, Deposition, Areal Extent / Location of Littoral Zone, Light Extinction	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Non-Point Nutrient & Organic Releases (upland or local land use)	↑ Nutrient Load, Rate of Organic Carbon Input, Heavy Metals, Eutrophication, Phytoplankton, Algae, Light Extinction	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae
Permitted Wastewater Discharge to Streams	↑ Nutrient Load, Rate of Organic Carbon Input, Heavy Metals, Aquatic Microorganisms, Eutrophication, Phytoplankton, Algae, Light Extinction	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae
Point Contaminant Releases (contaminated sites)	↑ Synthetic Organic Compounds, Petroleum Hydrocarbons, Heavy Metals, Pesticides, Wastewater Contaminants, & Other Toxic Substances (as applicable)	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Atmospheric Deposition	↑ Nitrogen & Sulphur Compounds, pH, Mercury & Other Metals, Pesticides (as applicable)	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Tamarisk	↑ Salinity	Tamarisk Abundance & Distribution; Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Other Exotic / Invasive Riparian Vegetation	Competition with Noninvasive Native Lacustrine Wetland Vegetation, ↓ or ↑ Bank Erosion, Sediment Load, △ Reservoir Morphology / Bed Composition, Lacustrine Wetland Habitat	Composition, Abundance, & Distribution of Lacustrine Wetland Vegetation, Macroinvertebrates, & Herptofauna
Exotic / Invasive Aquatic Vegetation	Competition with Noninvasive Native Aquatic Vegetation, △ Aquatic Habitat	Composition, Abundance, & Distribution of Aquatic Vegetation, Macroinvertebrates, Fish, & Herptofauna

Clearing of Emergent / Aquatic Vegetation & Woody Debris	Loss of Aquatic Habitat, ↓ Amphibians, Waterfowl, Fish Growth Rates, △ Water Quality	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Removal of Upland Riparian Vegetation	△ Sediment Load, Water Quality	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Exotic / Invasive Periphyton, Fish, or Herptofauna	Competition with Noninvasive Native Periphyton, Fish, and / or Herptofauna; △ Nutrient Cycling, Dissolved Oxygen	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Flood	△ Sediment Load, Water Quality, Water Temperature	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Drought	△ Water Quality, Water Temperature	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Climate Change (temperature, precipitation, wind)	↓ or ↑ Air & Water Temperatures, Reservoir Level, Nutrient Load, Sediment Load, Concentrations of Other Dissolved & Suspended Constituents	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae
Ungulate Grazing / Trampling	↑ Nutrient Load, Rate of Organic Carbon Input, Sediment Load, Phytoplankton, Algae, Light Extinction	Composition, Abundance, & Distribution of Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae
Swimming / Wading	Trampling of Aquatic / Lacustrine Wetland Vegetation, Loss of Habitat, ↑ Suspended Sediment	Composition, Abundance, & Distribution of Lacustrine Wetland Vegetation, Macroinvertebrates, & Herptofauna
Motorized Boating	↑ Suspended Sediment, Mobilization of Sorbed Contaminants, Petroleum Hydrocarbons	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna

Off-Road Vehicle Use	↑ Bank Erosion, Deposition, Light Extinction, △ Lacustrine Wetland Habitat	Composition, Abundance, & Distribution of Lacustrine Wetland Vegetation, Macroinvertebrates, & Herptofauna
Altered Fire Regime	↓ or ↑ Nutrient Load, Rate of Organic Carbon Input, Suspended Sediment, Phytoplankton, Algae, Light Extinction	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae

Table 12. Summary of stresses and indicators of reservoir ecosystem function and condition.

Stresses	Indicators
Surface Water Diversions (from reservoir or upstream tributaries)	Stream Discharge (Upstream Tributaries), Reservoir Level; Temperature Profile; Nutrients*1, BOD/COD*2, DO Profile*3, Water Clarity, Basic Water Quality Parameters*4; Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae
Groundwater Pumping	Groundwater Level, Stream Discharge (Baseflow to Upstream Tributaries), Reservoir Level; Temperature Profile; Nutrients*1, BOD/COD*2, DO Profile*3, Water Clarity, Basic Water Quality Parameters*4; Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae
Shoreline Development (buildings & other structures)	Reservoir Level; Bed Composition, Reservoir Morphometry*1; Suspended Sediment, Water Clarity, Basic Water Quality Parameters*4; Temperature Profile; Composition, Abundance, & Distribution of Littoral Zone Vegetation, Macroinvertebrates, & Herptofauna
Bank Stabilization	Bed Composition, Reservoir Morphometry*1; Suspended Sediment, Water Clarity; Composition, Abundance, & Distribution of Littoral Zone Vegetation, Macroinvertebrates, & Herptofauna
Bank Instability	Reservoir Morphometry*1; Suspended Sediment, Water Clarity; Composition, Abundance, & Distribution of Littoral Zone Vegetation, Macroinvertebrates, & Herptofauna
Dredging / Filling (Lacustrine Wetlands)	Reservoir Morphometry*1; Suspended Sediment, Water Clarity, Temperature Profile; Composition, Abundance, & Distribution of Littoral Zone Vegetation, Macroinvertebrates, & Herptofauna
△ Infiltration / Runoff Rates (due to changes in upland or local land use – e.g., urbanization or agricultural development)	Stream Discharge (Upstream Tributaries), Reservoir Level; Temperature Profile; Nutrients*1, BOD/COD*2, DO Profile*3, Water Clarity, Basic Water Quality Parameters*4; Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae

△ Sediment Load (due to changes in upland or local land use)	Bed Composition, Reservoir Morphometry*5; Suspended Sediment, Water Clarity; Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Non-Point Nutrient & Organic Releases (upland or local land use)	Nutrients*1, BOD/COD*2, DO Profile*3, Water Clarity, Basic Water Quality Parameters*4; Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae
Permitted Wastewater Discharge to Streams	Nutrients*1, BOD/COD*2, DO Profile*3, Water Clarity, Basic Water Quality Parameters*4, Aquatic Microorganisms*6; Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae
Point Contaminant Releases (contaminated sites)	Potential Point Source Contaminants*7, BOD/COD*2; Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Atmospheric Deposition	Nutrients*1, pH, Mercury & Other Metals, Pesticides (as applicable); Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Tamarisk	Tamarisk Abundance & Distribution; Reservoir Level; Stream Geomorphic Parameters*5; Salinity; Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Other Exotic / Invasive Riparian Vegetation	Suspended Sediment, Water Clarity; Bed Composition, Reservoir Morphometry*5; Composition, Abundance, & Distribution of Lacustrine Wetland Vegetation, Macroinvertebrates, & Herptofauna
Exotic / Invasive Aquatic Vegetation	Basic Water Quality Parameters*4, Nutrients*1; Composition, Abundance, & Distribution of Aquatic Vegetation, Macroinvertebrates, Fish, & Herptofauna
Clearing of Emergent / Aquatic Vegetation & Submerged Woody Debris	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation (and Woody Debris), Macroinvertebrates, Fish, & Herptofauna
Removal of Upland Riparian Vegetation	Suspended Sediment, Water Clarity; Bed Composition (Littoral Zone), Reservoir Morphometry*5; Basic Water Quality Parameters*4, Nutrients*1; Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna

Exotic / Invasive Periphyton, Fish, or Herptofauna	Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Macroinvertebrates, Fish, & Herptofauna
Flood	Stream Discharge (Upstream Tributaries), Reservoir Level; Bed Composition, Reservoir Morphometry*5; Suspended Sediment, Water Clarity, Nutrients*1, Basic Water Quality Parameters*4; Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Drought	Stream Discharge (Upstream Tributaries), Reservoir Level; Nutrients*1, Suspended Sediment, Water Clarity, Basic Water Quality Parameters*4; Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Climate Change (temperature, precipitation, wind)	Groundwater Level, Stream Discharge (Baseflow to Upstream Tributaries), Reservoir Level; Temperature Profile; Nutrients*1, BOD/COD*2, DO Profile*3, Water Clarity, Basic Water Quality Parameters*4; Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae
Ungulate Grazing / Trampling	Bed Composition (Littoral Zone), Reservoir Morphometry*5; Aquatic Microorganisms*6, Nutrients*1, BOD/COD*2, DO Profile*3, Suspended Sediment, Water Clarity; Composition, Abundance, & Distribution of Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae
Swimming / Wading	Aquatic Microorganisms*6, Suspended Sediment, Water Clarity; Composition, Abundance, & Distribution of Lacustrine Wetland Vegetation, Macroinvertebrates, & Herptofauna
Motorized Boating	Suspended Sediment, Water Clarity, Petroleum Hydrocarbons; Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna
Off-Road Vehicle Use	Suspended Sediment, Water Clarity; Bed Composition (Littoral Zone), Reservoir Morphometry*5; Composition, Abundance, & Distribution of Lacustrine Wetland Vegetation, Macroinvertebrates, & Herptofauna
Altered Fire Regime	Suspended Sediment, Water Clarity; Bed Composition, Reservoir Morphometry*5; Nutrients*1, BOD/COD*2, DO Profile*3, Basic Water Quality Parameters*4; Composition, Abundance, & Distribution of Aquatic / Lacustrine Wetland Vegetation, Macroinvertebrates, Fish, & Herptofauna; Abundance of Phytoplankton & Algae

*1 Nitrogen and phosphorous.

*2 Biological oxygen demand, chemical oxygen demand.

* 3 Dissolve oxygen profile.

*4 Water temperature, pH, dissolved oxygen, major cations and anions, conductivity, alkalinity, and turbidity.

*5 Reservoir mean / maximum depth, volume / area, depth profile / bed slope.

*6 Bacteria, viruses, and protozoa.

*7 Synthetic organic compounds, petroleum hydrocarbons, heavy metals, pesticides, and other toxic substances, as applicable

W.4. RIPARIAN ECOSYSTEM MODEL

The term riparian is derived from the Latin word *Riparius*, meaning the banks of a river or stream. Riparian zones occupy landscape positions that are transitional between upland and aquatic ecosystems and as a result are more physically dynamic and biologically diverse than surrounding uplands. Because of their unique landscape position, and tight linkages between fluvial and upland disturbance processes, riparian ecosystems are potentially sensitive indicators of landscape-level environmental change (Naiman et al. 1988). Riparian ecosystems are directly influenced by streams through enhanced water supply, flooding, and erosional and depositional processes (Brinson et al. 1981). At the same time, upland disturbance processes, across a range of scales, impose direct and indirect effects on riparian ecosystems. Debris flows and landslide disturbances impinge directly on narrow riparian zones on a local scale. At larger scales, the indirect effects of climate change and land use practices such as grazing and land-clearing, which degrade upland soil stability and reduce riparian vegetation cover, is to alter the delivery of water and sediment to receiving streams (Trimble and Mendel 1995).

W.4.1. Summary of Drivers, Stressors, Attributes, and Indicators of Riparian Ecosystem Function and Condition

Regional climate, atmospheric conditions, geology, landform, time, and upland watershed characteristics are drivers (major forces of change) for riparian ecosystems of the SOPN (Figure 13).

Due to the overriding importance of surface flow and groundwater dynamics on the establishment and survival of riparian plants, little work has focused on the effects of precipitation events as a driver of riparian vegetation dynamics. However, successful cottonwood recruitment has been correlated with wet years (Baker 1990), and workers on the San Pedro River in southern Arizona have shown correlations between precipitation and the richness and cover of some herbaceous riparian plant guilds (Bagstad et al. in press).

W.4.2. Riparian Ecosystem Function under Natural/Desired Conditions

Floods, alluvial groundwater, and riparian zone soils/morphology, major ‘soil-resources’ influencing the function of riparian ecosystems (Chapin et al. 1996), are described in this section, followed by a discussion of riparian biotic functional groups (vegetation, invertebrates, and vertebrates) and riparian ecosystem dynamics under natural/desired (sustainable) conditions. The attributes and functioning of SOPN riparian ecosystems under natural/desired conditions are summarized in Figure 14.

W.4.2.1. Riparian Water Resources

Floods - The reproductive traits of early successional riparian trees are tightly linked with fluvial disturbances. Seeds of *Populus* spp. and *Salix* spp. germinate and grow on moist, freshly deposited alluvial sediments following floods of appropriate timing, magnitude, and rate of recession (Mahoney and Rood 1998, Stromberg et al. 1991, Scott et al. 1997, Auble and Scott 1998, Cooper et al. 2003). The physical disturbance and increased moisture availability provided by floods is also positively associated with species richness and cover of herbaceous species in riparian zones. Whereas some studies have reported reduced diversity of riparian herbs following flooding (Smith et al. 1998), flood-related increases in the cover and diversity of annual and some perennial riparian herbs along the San Pedro River, Arizona, were attributed to the creation of safe sites for germination, increased water availability, and the possible transport of seeds and vegetative propagules by flood waters (Bagstad et al. in press). Flood transport of seeds, or hydrochory, may play an important role in maintaining high species diversity in riparian landscapes by preferentially delivering seeds of species, or groups of species, to specific riparian landscape positions at times suitable for establishment and growth.

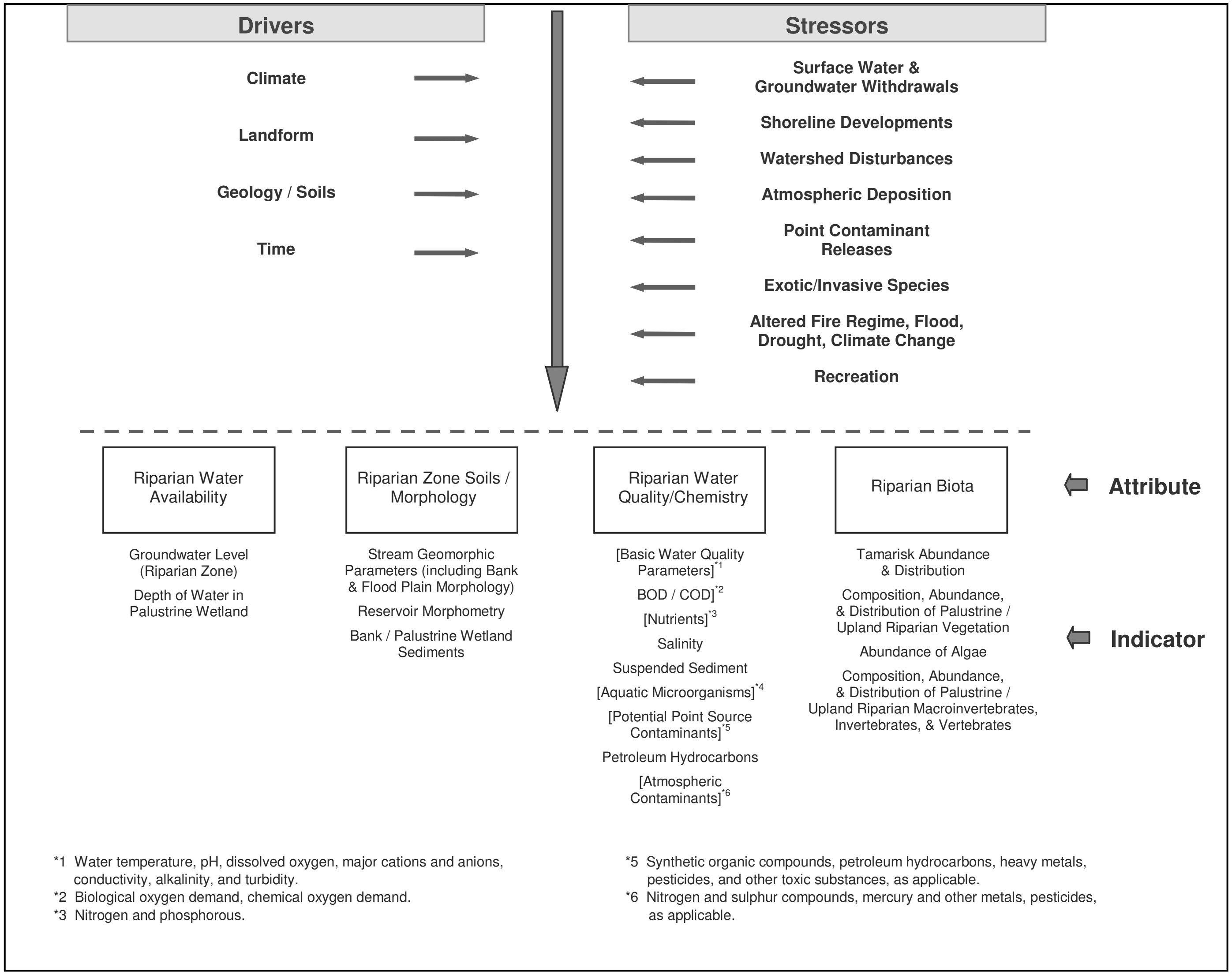


Figure 13. Overview of drivers, stressors, attributes, and indicators of riparian ecosystem function and condition.

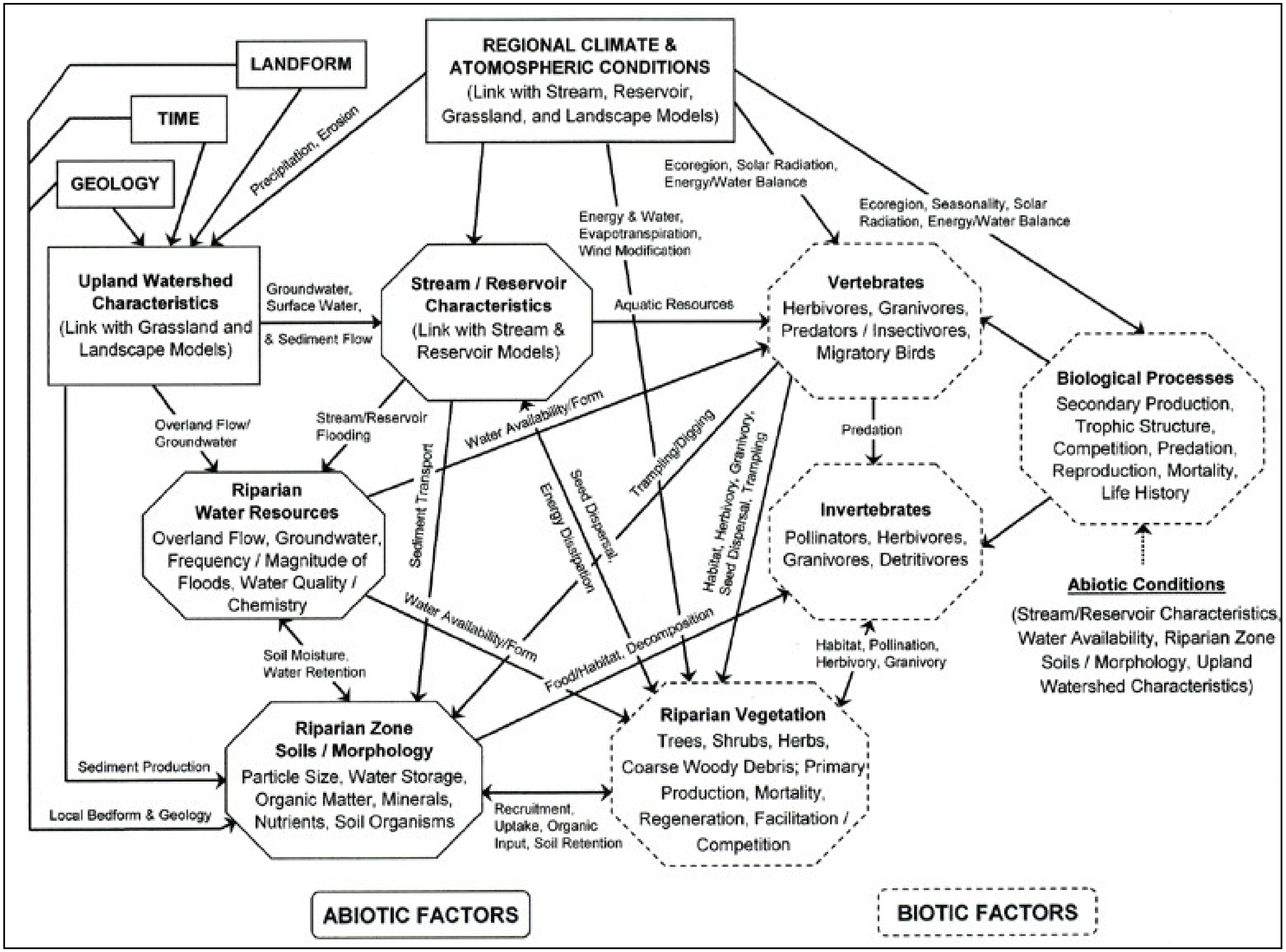


Figure 14. Natural/desired riparian ecosystem function. Modified from Scott et al. (2005).

Alluvial Groundwater - Water from surface flow and associated shallow alluvial aquifers is essential to the persistence of most low-elevation woody riparian species in the western U.S. Thus, an integrated understanding of surface and alluvial groundwater flows, and their interactions, is fundamental to understanding the establishment and survival processes of existing riparian and wetland ecosystems (Winter 1999, Woessner 2000). On coarse substrates in dry regions, early establishment and growth of *Populus* spp. seedlings, and other woody riparian pioneer species, may require groundwater within 1-2 m of the establishment surface (McBride and Strahan 1984, Mahoney and Rood 1992, Segelquist et al. 1993, Stromberg et al. 1996), but lenses of finer alluvial material may allow seedlings to survive the first few growing seasons without making contact with groundwater (Cooper et al. 1999). Following initial establishment, root growth allows young trees to survive gradual groundwater declines. Depth to groundwater may increase as a result of subsequent floodplain accretion or channel incision (Everitt 1968, Hereford 1986), and *Populus* species have been observed at sites where depth to groundwater is 7 - 9 m (Robinson 1958). However, mature native riparian species such as *Populus*, *Salix* and *Tamarix* are typically found in riparian settings where depth to water is < 4 m (Meinzer 1927, Busch et al. 1992, Scott et al. 1997, Stromberg et al. 1997, Horton et al. 2001a).

Alluvial groundwater is the principle source of water for riparian trees (Busch et al. 1992, Snyder and Williams 2000). Even relatively modest fluctuations or declines (1.5-3 meters) can induce lethal moisture stress (Scott et al. 1999, Shafroth et al. 2000). Seasonal groundwater declines of 2.5-3 meters, in a dry year, along the free-flowing Hasayampa River, Arizona, produced moisture stress in the native riparian cottonwood (*Populus fremontii*), and willow (*Salix gooddingii*) and non-native tamarisk (*Tamarix ramosissima*). All species responded to this stress with lowered shoot water potentials, decreased leaf gas exchange rates, increased canopy die-back, and some tree mortality. Compared to native riparian trees, however, tamarisk had much higher rates of leaf gas exchange and stem growth under shallow groundwater conditions, and exhibited less crown die-back and mortality when groundwater declined. The combination of high leaf gas exchange rates and stem growth when water is available, and greater moisture stress tolerance under dry conditions, help explain the competitive success of tamarisk in southwestern riparian ecosystems, particularly those subject to large within and across-year fluctuations in water availability (Horton 2001b).

W.4.2.2. Riparian Zone Soils/Morphology

Floodplain Soils - The soils of a riparian ecosystem differ from those of both upland systems and permanently flooded bottomlands. Shallow alluvial groundwater is a unique and important functional feature of riparian floodplain soils, and is tightly linked to surface water dynamics. Native and non-native woody phreatophytes, like cottonwood, willow and Tamarisk are dependent, to varying degrees, upon shallow alluvial groundwater sources, and spatially complex moisture gradients resulting from floodplain topographic diversity and surface and groundwater dynamics. These factors influence the diversity of herbaceous riparian plants and soil organisms (Meinzer 1927, Scott et al. 1997, Stromberg et al. 1997, Pollock et al. 1998, Horton et al. 2001a, Bagstad et al. in press, Beauchamp 2004).

Because of their dynamic nature, floodplain soils in drier regions of the United States are typically young and poorly developed, often lacking the distinct horizons of soil formed by the interaction of weathering processes and living organisms over time. Many of these soils lack an aquic moisture regime, which requires that soils be saturated long enough to become anoxic and to develop distinctive redoximorphic features such as gleying (Brady 1974). The combination of fine-textured soils, high organic matter and nutrient content, alternating periods of wetting and drying, and anaerobic versus aerobic conditions which make floodplain soils in more humid regions biogeochemically dynamic, are generally lacking in western floodplain soils (Mitsch and Gosselink 1993). In drier riparian ecosystems, nutrient availability is more closely related to nutrient flux in streamflow than soil stores, although these fluxes are poorly understood (Schade et al. 2002). Freshly deposited alluvial sands are typically low in nitrogen and riparian plants colonizing these surfaces are nitrogen-limited (Adair and Binkley 2002). In general, the periodic wetting and drying of riparian soils is considered important in the release of nutrients from leaf litter in riparian environments (Mitsch and Gosselink 1993).

Soil biota represent another broadly defined group of organisms that is an important contributor to the structure and functioning of riparian ecosystems. Most of the ecosystem soil processes (i.e., nutrient cycling, water infiltration and storage, soil aggregate stability, water and nutrient uptake by plants) are mediated by soil organisms (Skujins 1984; Whitford 1996, 2002; Lavelle 1997; Wardle 2002). Although the general significance of soil biota for ecosystem processes (particularly nutrient cycling) has long been acknowledged, there is increasing recognition that this diverse group of organisms must be considered more explicitly in order to develop a better understanding of the structure and functioning of terrestrial (Wardle 2002, Reynolds et al. 2003) and riparian ecosystems. Because of their intimate association with other components of riparian ecosystems, soil organisms are included in Figure 13 as a component of floodplain soils.

Soil biota include microfloral components (bacteria, algae, and fungi), microfaunal components (nematodes, microarthropods, and protozoans), and macrofaunal components (earthworms, ants, termites, and larval stages of several insect families) that are involved in a variety of processes essential for litter decomposition and nutrient cycling. Functioning of these belowground processes is dependent on the amounts and types of organic-matter inputs from vegetation and soil conditions such as moisture availability (which is strongly influenced by surface and groundwater dynamics), soil structure, soil aeration, and soil temperature (Whitford 1996, 2002; Mitsch and Gosselink 1993).

Mycorrhizal fungi, which form symbiotic associations with roots of many plant species, are another important element of the soil biota. The mycorrhizal symbiosis is one in which the fungal partner provides nutritional benefits to the host plant, and the plant provides carbohydrates to the fungi (Smith and Read 1997). Roots colonized by mycorrhizal fungi acquire phosphorus, zinc, and possibly copper and nitrogen more efficiently than uncolonized roots. There is also evidence that mycorrhizae can increase water uptake in plants due to greater soil volume accessed by colonized roots (Smith and Read 1997). Arbuscular mycorrhizal fungal communities have been described for a number of ecosystems, however comparatively little is known about the structure and composition of these communities in riparian ecosystems. Recent work in cottonwood/willow forests along regulated and unregulated reaches of the Verde River, Arizona, indicates that fungal colonization rates and diversity increases with increases in the diversity of perennial species and decreased with increases in stand age, as well as distance from and elevation above the channel. Stand age, soil moisture and soil texture appeared to be important environmental determinants of fungal community structure, and whereas most species found in these riparian settings are also found in adjacent uplands, diversity was higher in the riparian zone and two species were restricted to these sites (Beauchamp 2004).

Some species common to riparian ecosystems have been identified as mycorrhizal when inspected by botanists (Trappe 1981). Families with a high frequency of mycorrhizal colonization among inspected species included the Asteraceae, Fabaceae, Rosaceae, Poaceae, and Solanaceae. The Brassicaceae stands out as a relatively common riparian plant family in which most inspected species were nonmycorrhizal (Trappe 1981).

Riparian Zone Morphology - Flood plains represent one of a number of river-deposited features and are typically composed of vertically stacked fine grained layers left by discrete floods. By definition, flood plains are level surfaces constructed by a river under prevailing climatic conditions, and are frequently inundated by high flows (Leopold 1994). Riparian vegetation establishment and succession is intimately linked to the lateral and vertical accretion of sediments that lead to floodplain formation across a range of channel forms (Schumm and Lichty 1963, Hereford 1984, Bradley and Smith 1986, Boggs and Weaver 1994). This linkage between fluvial geomorphic processes and riparian vegetation dynamics creates the topographic diversity, soil moisture gradients, fluvial disturbance patches, and distinctive microclimates that characterize riparian ecosystems. The spatial extent of floodplains along streams of the Southern Plains is highly variable and dependent on geomorphic setting. Along channels confined by colluvial materials or bed rock, floodplain deposits may be narrow and discontinuous, or even non-existent. In contrast, channels in large alluvial basins may have large, spatially extensive flood plains.

W.4.2.3. Riparian Vegetation

At a broad level, vegetation is generally recognized as *the* dominant functional type in riparian ecosystems. In addition to conducting photosynthesis, the aboveground structure of vascular plants increases roughness and thus protects floodplain soils from erosion and enhances the deposition and retention of nutrient-rich sediments during floods. Litter from plants reduces the erosive impacts of rainfall on soil surfaces and provides inputs to soil organic matter for nutrient cycling. Aboveground structures of riparian plants modify the physical environment by shading and litter deposition, strongly affecting spatial and temporal patterns of soil-resource availability for other organisms. Vegetation structure helps create gradients of moisture and temperature that are important to maintaining biotic diversity. Roots stabilize soils and stream-banks are conduits for resource acquisition and redistribution, and provide organic-matter inputs to soil food webs. Vegetation also provides fuel for fire, as well as resources and habitat structure for belowground and aboveground consumers and decomposers ranging from fungi and bacteria to birds and mammals (Brinson et al. 1981, Whitford 2002, Wardle 2002). Finally, carbon storage and the mediation of earth-atmosphere energy/water balances are additional ecosystem functions performed by vegetation that are increasingly important with respect to global-change processes (Breshears and Allen 2002, Asner et al. 2003).

A large number of vegetation attributes affects the manner and extent to which these functions are performed. Size, biomass, photosynthetic rate, relative and absolute growth rates, tissue chemistry, stem basal area, canopy cover, vertical canopy structure, spatial arrangement and contiguity, leaf area, leaf longevity, and plant life-span are some of the more important vegetation attributes for ecosystem functioning (Chapin 1993). Root distribution, reproductive traits, moisture requirements, and phenology are additional functional attributes of vegetation that are particularly important in riparian ecosystems. With respect to disturbance interactions, important functional attributes include palatability, flammability, and mode of post-disturbance regeneration.

Woody trees and shrubs are the defining structural and functional elements of riparian ecosystems, especially in dry landscapes (Mitsch and Gosselink 1993). The two most frequently occurring native tree genera in riparian ecosystems of the western U.S. are *Populus* and *Salix*. The non-native trees, tamarisk (*Tamarix*) and Russian-olive (*Elaeagnus*), represent the third and forth most frequently occurring riparian genera (Friedman et al. in press).

Provision of habitat for a diverse array of secondary consumer and decomposer communities is an important functional attribute of riparian vegetation. Undisturbed riparian ecosystems are recognized as being especially diverse biologically. The importance of riparian ecosystems in this regard is attributed to a unique combination of physical and biological characteristics, including: (1) a predominance of woody plants; (2) at least a seasonal presence of surface water and high soil moisture; (3) an interspersion of diverse structural elements that create high habitat patch diversity; and (4) a linear form with high connectivity, that provides for uniform, protected pathways for migration and movements between different habitat types (Brinson et al. 1981).

Many of the functional attributes described above differ greatly among vegetative life forms. For example, there are relatively large differences among riparian trees, shrubs and herbs in terms of canopy height, architecture and spatial arrangement, as well as in their responses to climate, fire and herbivory. As a consequence, ecosystems characterized by different proportions of trees, shrubs, herbs, and grasses can be expected to differ greatly in terms of associated ecosystem processes including nutrient cycling, hydrologic regimes, disturbance regimes, and wildlife-habitat relationships. Likewise, temporal shifts in the relative abundance and spatial configuration of vegetative life forms can significantly affect the functioning of an array of ecosystem processes.

W.4.2.4. Riparian Zone Invertebrates and Vertebrates

The presence of water, nutrient-rich soils, and the interspersion of a variety of successional aquatic and terrestrial biotic communities make riparian zones more productive and biologically diverse than surrounding uplands (Lugo et al. 1990; Knutson et al. 1996). The physical and biotic components of riparian ecosystems have important influence on the biota of stream ecosystems, but here we focus on non-aquatic invertebrate and vertebrate communities. Vertebrate and invertebrate communities are significant contributors to the biological diversity of aquatic and riparian ecosystems (e.g., Stevens et al. 1977, Brode and Bury 1984, Falck et al. 2003, Fleishman et al. 1999). There are numerous ways in which above-ground, consumers can directly or indirectly affect the structure and functioning of riparian ecosystems. Activities associated with herbivory, trampling, and ponding are among those that have the greatest ecosystem-level consequences for riparian and aquatic ecosystems due to their many effects on vegetation structure and floodplain soil processes. Processes of competition and predation can likewise have important ecosystem-level consequences by altering the structure of consumer food webs, but these processes are not reviewed here.

Herbivory can have numerous direct and indirect effects on ecosystem properties. Native herbivores in riparian ecosystems of the region include insects (grasshoppers and others) and mammals such as beaver (*Castor canadensis*), mice, voles, and deer. Herbivorous insects and small to medium-sized mammals can have significant effects on riparian and wetland vegetation structure, reproductive patterns, and ecosystem processes such as decomposition and nutrient cycling (Wallace and O'Hop 1985, Scott and Haskins 1987, Anderson and Cooper 2000). Perhaps the greatest ecosystem-level consequences for riparian ecosystems are those associated with biophysical alterations, such as dam building by beaver and structural habitat modifications resulting from herbivory and trampling, caused by large-bodied browsers and grazers, including deer and domestic livestock. At certain levels, these activities contribute to the overall biodiversity of riparian ecosystems by creating a dynamic mosaic of different habitat patch types (Naiman and Rogers 1997). However, chronic, high densities of large-bodied browsers and grazers may ultimately lead to habitat simplification and loss of biodiversity (Kauffman and Krueger 1984, Taylor 1986, Scott et al. 2003).

Large herbivores can affect individual plants both directly and indirectly through a variety of mechanisms. Direct impacts include altered physiological function and morphology attributable to defoliation and trampling (Briske 1991, Briske and Richards 1995). Defoliation and trampling by large herbivores may indirectly influence plant performance as a consequence of altered microenvironmental conditions, soil properties (Thurow 1991), mycorrhizal relations (Bethlenfalvay and Dakessian 1984), competitive relations, and through effects on ecosystem processes such as nutrient cycling and channel and floodplain formation. Seed dispersal is yet another indirect mechanism by which large herbivores and other animals may affect vegetation structure. Through time, combined direct and indirect impacts can result in altered plant population dynamics (e.g., altered rates of reproduction, recruitment, and mortality) and consequent changes in plant community composition, structure, and distribution (Brinson et al. 1991, Naiman and Rogers 1997). Due to strong interactions of vegetation with nutrient cycling, hydrologic processes, disturbance regimes, and geomorphic processes, herbivore-driven changes in vegetation structure can have cascading effects on multiple ecosystem processes and properties.

Large herbivores can also affect the productivity and composition of plant communities through numerous indirect and direct effects on nutrient cycling in upland (Archer and Smeins 1991) and riparian systems. Herbivore-driven shifts in plant community structure can affect nutrient cycles by altering the capacity of vegetation to capture and retain soil and water resources (Whitford 2002) and by altering the quantity and quality of organic-matter inputs (Bardgett and Wardle 2003). Herbivory removes foliage and directly diverts nutrients from litter and physiological processes of intra-plant cycling. Nutrients acquired from foliage may be incorporated in animal biomass or spatially redistributed across the landscape in urine and dung. Where excreta are deposited, productivity may be enhanced if nutrients contained in the excreta are accessible to nearby plants. In other portions of the landscape, productivity may be reduced due to the removal of nutrients in the form of foliage.

W.4.2.5. Riparian Ecosystem Dynamics

Within riparian corridors, the availability of water and nutrient rich soils, along with relatively frequent fluvial disturbance, contribute to high rates of productivity and confer both resistance and resilience to natural disturbance processes (Stromberg et al. 1993). In addition, uniquely high levels of biological diversity associated with riparian ecosystems are attributed to variation in the frequency and intensity of flooding, larger-scale variations in climate as streams traverse elevational gradients, smaller-scale topographic diversity and related soil and moisture gradients, and upland disturbance processes, which together, produce a diverse array of habitat patch types (Naiman et al. 1993).

Early successional woody riparian species like cottonwood and willow, as well as a host of herbaceous species, are disturbance-dependent, requiring bare, moist stream deposits for seed germination and establishment. Thus, models of riparian ecosystem dynamics begin with un-vegetated alluvial landforms which are typically colonized by cottonwood, willow species, and grasses. These early successional vegetation patches are either replaced by later successional riparian or upland species, or returned to bare alluvium by intense fluvial disturbance (Johnson 1994, Friedman et al. 1997, Richter and Richter 2000).

Two physical environmental gradients have been shown to influence riparian ecosystems at different scales; longitudinal, or up/down valley gradients, and transverse, or cross-valley gradients. Longitudinal-scale variables including elevation, valley slope, valley width, and lithology, influence riparian ecosystem dynamics at larger spatial scales. Whereas smaller, transverse-scale variables include depth to the water table, flood frequency, flood intensity, and substrate texture (Bendix 1994). We briefly illustrate the influence of these factors on riparian ecosystem dynamics and diversity.

W. 4.3. Natural and Anthropogenic Stresses and Riparian Ecosystem Response

Significant changes in any of the four interactive controls (Chapin et al. 1996) are predicted to result in a new ecosystem with different characteristics than the original system. Major changes in flow regime can be expected to greatly affect vegetation establishment and survival patterns, productivity, and competitive interactions among species, and thus cause significant changes in the structure and functioning of riparian plant communities and higher trophic levels. Changes in vegetation composition and structure can affect the ecosystem's disturbance regime (e.g., through altered fire frequency and intensity). These factors, in combination with processes, can result in an altered system which is fundamentally different from the original riparian system in terms of composition, structure, functioning, and dynamics.

This section describes predominant natural and anthropogenic stressors affecting the structure and functioning of riparian ecosystems of the Southern Plains, and presents conceptual models of degradational processes related to those stressors.

W.4.3.1. Streamflow Alteration

Flow Depletion - Flow depletions resulting from the diversion of streamflow, can have a range of effects on aquatic and riparian ecosystems. When depletions are small and incremental, effects on riparian ecosystems may be subtle, involving reduced over-bank flooding, loss of species richness, reduced site productivity, structural simplification, such as reduced tree height and density, reductions in the creation of new riparian vegetation patches, and increased susceptibility to fires. However, significant depletions of surface and groundwater can lead to dewatering of the channel and floodplain, resulting in the mortality of riparian vegetation and encroachment of upland vegetation and/or non-native weeds. This terrestrialization of the riparian zone is a common transition pattern in riparian ecosystems and the predicted outcome of reductions in flow variability and/or flow volume (Auble et al. 1997, and *in press*). The degree of terrestrialization may signal the extent to which riparian ecosystems have been altered by water management activities (Innis et al. 2000). Decreased bank stability associated with the loss of riparian vegetation makes these sites prone to channel incision and ultimately the loss of flood plain soils, site conditions that typically support riparian and aquatic ecosystems (Rood and Mahoney 1990, Kondolf and Curry 1986).

Altered Flow Variability - Physical changes resulting from flow alteration downstream of large dams typically degrades the biotic integrity of riparian ecosystems by altering habitats and competitive interactions in favor of non-native riparian species. The loss of ecological integrity resulting from streamflow alteration is illustrated by a widespread degradational process involving the conversion of riparian cottonwood-willow forest to woodlands dominated by the non-native riparian tree, *Tamarix ramosissima*. This represents a common transition in riparian zones throughout the western US (Friedman et al., in press). The mechanisms apparently responsible for such transitions involve reductions in streamflow and channel narrowing resulting from reduced sediment transport. Establishment of relatively dense stands of tamarisk on un-vegetated portions of the formerly active channel facilitates narrowing through the vertical accretion of sediments and flood plain formation. Although climate-related fluctuations in precipitation have been implicated as a principle cause of channel narrowing along some un-dammed rivers (Hereford 1984), damming and diversion of streamflow have facilitated transitions to tamarisk in many cases. In fact, both climate and flow regulation have likely acted in concert, to varying degrees on different streams, to produce this transition (Alred and Schmidt 1999, Grams and Schmidt 2002). High salinity levels, either natural or human-induced (e.g., by irrigation return flows), may also favor the establishment of tamarisk over native species (Shafroth et al. 1995). This conversion may also be self-promoting to the degree that tamarisk increases the frequency and intensity of fires, and re-sprouts more effectively following fire than native riparian species like cottonwood (Ohmart and Anderson 1982, Busch and Smith 1995).

Floods - High magnitude floods can produce dramatic, long-term transformations in riparian ecosystem structure and functioning by inducing widespread geomorphic changes and plant mortality that may in turn initiate extended episodes of establishment of relatively long-lived alternative riparian species (Schumm and Lichty 1963). That is, individual floods may influence the reproductive patterns of riparian species for decades following a flood event. Along numerous western streams, channel narrowing and floodplain formation since the 1940's, has been accompanied by the establishment of extensive stands of saltcedar (primarily *Tamarix ramosissima*; Burkham 1972, Hereford 1984). The degree to which saltcedar has facilitated such narrowing is the nexus of a long-standing debate (Graf 1978, Everitt 1980). However, the regional nature of channel narrowing and floodplain construction has led Hereford (1987) to conclude that this channel-change process is primarily due to the control of larger-scale factors such as climate.

Drought - The effects of regional climatic drought on riparian ecosystems are expressed most directly through reduced surface flows and depletion of alluvial groundwater aquifers. Thus, the stress effects of naturally occurring drought mimic those produced by anthropogenic stressors such as damming and diversion of streamflow, groundwater pumping, and channel incision resulting from altered flows of water and sediments, bank stabilization, and in-stream gravel mining (Bravard et al. 1997, Kondolf 1994, 1997, Rood et al. 1995, Stromberg et al. 1996, 1997, Scott et al. 2000).

The response of any plant to gradually increasing water stress involves progressive and integrated physiological and morphological responses, beginning with stomatal closure, reduced leaf and canopy development, and ending with death (Bradford and Hsiao 1982, Braatne et al. 1992). Mild water stress can reduce plant productivity by limiting CO_2 assimilation through stomatal closure, lowering net photosynthesis, and through the death of leaves and fine roots. Under more severe drought conditions, trees exhibit reduced radial stem increments, wilting and abscission of leaves, and branch death. Tree mortality may follow directly or secondarily as the result of insects or other pathogens (Albertson and Weaver 1945). Because these changes occur at different levels of water stress and on different time scales, accurate quantification of longer-term water stress is problematic (Pallardy et al. 1991).

Despite widespread occurrence in semiarid landscapes, riparian cottonwood species are susceptible to drought-induced cavitation of xylem vessels (Tyree et al. 1994), and suffer higher mortality during drought than several eastern deciduous forest species (Kaylor et al. 1935, Albertson and Weaver 1945) or non-native tamarisk (Busch and Smith 1995, Cleverly et al. 1997, Horton 2001a, b). In water stressed cottonwood species, Smith et al. (1991) found significantly reduced stomatal conductance and reduced midday leaf water potential (Ψ_l) for *Populus trichocarpa* compared with non-stressed trees. These trends were particularly pronounced for juvenile trees. Busch and Smith (1995) found moderately higher rates of stomatal conductance and transpiration and slightly higher predawn and midday Ψ_l in comparing *Populus fremontii* and *Salix gooddingii* from a gaining reach with those from a losing reach of the Bill Williams River, Arizona. Riparian *Populus* can exhibit morphological and growth responses to chronic water stress, including reduced leaf size, increased leaf thickness, reduced leaf area, reduced annual stem elongation, and reduced radial stem increments (Smith et al. 1991, Stromberg and Patten 1991, Busch and Smith 1995). Under conditions of acute water stress associated with severe climatic drought or water table declines, *Populus* display more extreme morphological responses such as crown die-back (branch sacrifice), and ultimately stand mortality (Ellison and Woolfolk 1937, Albertson and Weaver 1945, Stromberg 1993, Rood et al. 1995, Rood et al. 2000).

Availability of Alluvial Groundwater - The rate, depth, and duration of alluvial groundwater declines and the water holding characteristics of the soil interact with atmospheric water demand (i.e., temperature, humidity, wind speed) to influence the intensity and duration of water stress in groundwater-dependent plants. The few studies that quantitatively link alluvial groundwater dynamics to riparian vegetation response suggest that along rivers in semi-arid regions: (1) woody riparian trees are sensitive to seasonal or longer-term alluvial groundwater declines (Groeneveld and Griepentrog 1985, Stromberg et al. 1996), (2) they exhibit moisture stress responses ranging from short-term physiological adjustments to stand-wide mortality (Busch et al. 1995, Scott et al. 1999, Shafroth et al. 2000, Horton 2001a,b), (3) stress responses can be deferred by short-term increases in streamflow and corresponding rises in the groundwater (Cooper et al. 2003), (4) tree physiological condition deteriorates rapidly when groundwater declines cross a threshold depth ranging from 5-10 feet (1.5-3 m) (Scott et al. 1999, Shafroth et al. 2000, Horton 2001a), (5) non-native tamarisk is more tolerant of groundwater-induced moisture stress than native cottonwoods and willows (Busch and Smith 1995, Cleverly et al. 1997, Shafroth et al. 2000, Horton 2001b), and (6) the intensity of physiological responses appears to be conditioned by the influence of the historical, site-specific groundwater regime on root architecture (Shafroth et al. 2000, Scott et al. 2000).

W.4.3.2. Alteration of Riparian Zone Soils/Morphology

Abrupt changes in stream channel patterns, from straight through braided forms, can occur in response to a range of factors, as critical geomorphic thresholds are exceeded by changes in external variables such as stream power, channel gradient, and sediment transport (Schumm and Kahn 1972), accompanied by changes in riparian zone morphology. Such channel pattern-shifts can be triggered by episodic events, which may have long-lasting effects on stream and valley morphology, erosional and depositional processes, and riparian and aquatic ecosystems. Rare, large floods have eroded flood plains and terraces and transformed meandering channels near the threshold of pattern-change to a braided pattern. Subsequent channel narrowing and re-establishment of a meandering channel form can then occur through the process of flood plain construction and the establishment of riparian vegetation on portions of the former channel bed (Schumm and Lichty 1963, Friedman et al. 1996). Channel narrowing can also result from the widespread establishment of tamarisk. However, more often than not, significant changes in stream morphology, which give rise to changes in riparian zone morphology, are the result of changes in local land use (e.g., grazing practices) or small instream structures such as check dams and low-water bridges.

Vertically aggraded floodplains progressively become disconnected from surface flows in adjacent channels, and may be abandoned if the regional climate becomes drier. Abandoned flood plains are referred to as terraces. Remnant terrace sequences from across the arid and semi-arid western United States record several climatically driven valley cut-and-fill cycles during the Holocene period (within the last 10,000 years). These changes have dramatic effects on rivers and their floodplains. Geologic evidence indicates that during relatively cool, wet periods, valleys fill by deposition of alluvial (river-derived) sediments. When a period of deposition is followed by a relative dry period, the channel incises into the alluvium, abandoning the previously constructed floodplain as a terrace. Whereas valley deposition or aggradation is a slow process (thousands of years), corresponding valley erosion and floodplain abandonment is rapid (tens to hundreds of years) (Leopold 1994).

W.4.3.3. Ungulate Grazing and Trampling

Because of the presence of water and shade, riparian areas are often subject to more intense grazing pressure than adjacent uplands (Platts 1991). Long-term grazing by livestock and other large herbivores can have profound on-site impacts on riparian ecosystems including the removal of plant biomass, alteration of plant population age structures, and simplification of plant compositional and structural diversity (Szaro and Pace 1983, Kauffman and Kruger 1984, Schultz and Leininger 1990). These changes in turn are related to reduced abundance and diversity of riparian-dependent species, including birds (Taylor 1986, Dobkin et al. 1998, Scott et al. 2003). Within riparian zones, grazing reduces the erosional resistance of alluvial surfaces by reducing vegetation cover. Trampling directly erodes and destabilizes alluvial surfaces, making them prone to further erosion during high flows (Trimble and Mendel 1995).

The riparian plant community controls the amount of light reaching the stream surface, and strongly influences nutrient cycling and transport, organic matter input, bank stability, and stream channel morphology, as well as subsurface flow to streams (Gregory et al. 1991). If vegetation is reduced, light and temperature increase, which may result in greater algal growth.

Stresses and impacts on the availability of water in riparian zones, riparian zone soils and morphology, riparian water quality/chemistry (including palustrine wetlands), and riparian zone biota in SOPN parks are enumerated in Tables 13 through 16, respectively, accompaned by indicators of ecosystem response/condition. For each major stressor identified, indicators of ecosystem condition are summarized in Table 17.

Table 13. Stresses and impacts on the availability of water in the riparian zone

Stresses	Effects	Indicators
Surface Water Diversions (△ Streamflow)	↓ Stream Stage / Reservoir Level, Riparian Water Table / Depth of Water in Palustrine Wetlands	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland
Groundwater Pumping (△ Baseflow, Streamflow)	↓ Groundwater Level (Regional), Stream Stage / Reservoir Level, Riparian Water Table / Depth of Water in Palustrine Wetlands	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland
△ Local Stream Base Level(s)	↓ or ↑ Stream Stage, Riparian Water Table / Depth of Water in Palustrine Wetlands	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland
Impoundments	↑ Stream Stage, Riparian Water Table / Depth of Water in Palustrine Wetlands	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland
Shoreline Development (buildings & other structures)	↑ Overland Flow, Stream Stage / Reservoir Level, Depth of Water in Palustrine Wetlands	Depth of Water in Palustrine Wetland
△ Infiltration / Runoff Rates (due to changes in upland or local land use – e.g., urbanization or agricultural development)	↓ or ↑ Groundwater Level (Regional), Stream Stage / Reservoir Level, Riparian Water Table / Depth of Water in Palustrine Wetlands	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland
Tamarisk & Other Phreatophytes	↑ Evapotranspiration, ↓ Stream Stage / Reservoir Level, Riparian Water Table / Depth of Water in Palustrine Wetlands	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland
Removal of Upland Riparian Vegetation	↓ Evapotranspiration, ↑ Stream Stage / Reservoir Level, Riparian Water Table / Depth of Water in Palustrine Wetlands	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland
Flood	↑ Stream Stage / Reservoir Level, Riparian Water Table / Depth of Water in Palustrine Wetlands	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland

Drought	↓ Stream Stage / Reservoir Level, Riparian Water Table / Depth of Water in Palustrine Wetlands	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland
Climate Change (temperature, precipitation, wind)	↓ or ↑ Stream Stage / Reservoir Level, Riparian Water Table / Depth of Water in Palustrine Wetlands	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland
Fragmentation (including stream downcutting & floodplain / palustrine wetland abandonment)	↓ Frequency of Flooding, Exchange of Surface Water in Fragmented Palustrine Wetlands; (where stream is downcut) ↓ Riparian Water Table / Depth of Water in Palustrine Wetlands	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland

Table 14. Stresses and impacts on riparian zone soils / morphology

Stresses	Effects	Indicators
Surface Water Diversions (△ Streamflow)	Stream Riparian: ↓ Streamflow, △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Floodplain / Bank Composition	Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology)
Groundwater Pumping (△ Baseflow, Streamflow)	Stream Riparian: ↓ Baseflow / Streamflow, △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Floodplain / Bank Composition	Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology)
△ Local Stream Base Level(s)	Stream Riparian: △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Floodplain / Bank Composition	Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology)
Impoundments	Stream Riparian: △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Floodplain / Bank Composition	Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology)
Shoreline Development (buildings & other structures)	Stream or Reservoir Riparian: Bank Modification	Stream Geomorphic Parameters[*1] (including Floodplain Morphology) or Reservoir Morphometry[*2] (including Palustrine Wetlands)
Bank Stabilization / Channel Straightening	Stream Riparian: △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Floodplain / Bank Composition Reservoir Riparian: △ Bank Morphology, Bank Composition	Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology) or Reservoir Morphometry[*2] & Bank Composition
Bank Instability	Reservoir Riparian: △ Bank Morphology	Reservoir Morphometry[*2] (Bank Slope)
Dredging / Filling (palustrine wetlands)	Stream Riparian: △ Palustrine Wetland Morphology Reservoir Riparian: △ Palustrine Wetland Morphology	Stream Geomorphic Parameters[*1] (including Floodplain Morphology) or Reservoir Morphometry[*2] (including Palustrine Wetlands)

△ Infiltration / Runoff Rates (due to changes in upland or local land use – e.g., urbanization or agricultural development)	Stream Riparian: △ Baseflow / Streamflow, Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Bed Composition	Stream Geomorphic Parameters*1 (including Bank & Floodplain Morphology)
△ Sediment Load (due to changes in upland or local land use)	Stream Riparian: △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Floodplain / Bank Composition Reservoir Riparian: △ Deposition, Reservoir Morphology / Bank Composition	Stream Geomorphic Parameters*1 (including Bank & Floodplain Morphology) <u>or</u> Reservoir Morphometry*2 (including Palustrine Wetlands) & Bed Composition
Tamarisk	Stream Riparian: △ Stream Cross-Sectional Geometry (loss of active channel) Reservoir Riparian: △ Reservoir Morphology (decreased deep water habitat)	Stream Geomorphic Parameters*1 (including Bank & Floodplain Morphology) <u>or</u> Reservoir Morphometry*2 (including Palustrine Wetlands)
Other Exotic / Invasive Riparian Vegetation	Stream or Reservoir Riparian: ↓ or ↑ Bank Erosion, Sediment Load, △ Stream Geomorphology / Reservoir Morphology	Stream Geomorphic Parameters*1 (including Bank & Floodplain Morphology) <u>or</u> Reservoir Morphometry*2 (including Palustrine Wetlands) & Bank Composition
Removal of Upland Riparian Vegetation	Stream or Reservoir Riparian: ↑ Bank Erosion, Sediment Load, △ Stream Geomorphology / Reservoir Morphology	Stream Geomorphic Parameters*1 (including Bank & Floodplain Morphology) <u>or</u> Reservoir Morphometry*2 (including Palustrine Wetlands) & Bank Composition
Flood	Stream Riparian: Possible △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Floodplain / Bank Composition	Stream Geomorphic Parameters*1 (including Bank & Floodplain Morphology)
Climate Change (temperature, precipitation, wind)	Stream Riparian: △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Floodplain / Bank Composition	Stream Geomorphic Parameters*1 (including Bank & Floodplain Morphology)

Ungulate Grazing / Trampling	Stream Riparian: Trampling of Riparian Vegetation & Banks, ↑ Sediment Load, △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Floodplain / Bank Composition Reservoir Riparian: Trampling of Riparian Vegetation & Banks, ↑ Sediment Load, △ Bank Morphology, Bank Composition	Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology) or Reservoir Morphometry[*2] (including Palustrine Wetlands) & Bank Composition
Instream Driving / Vehicle Crossing	Stream Riparian: △ Stream Cross-Sectional Geometry, ↑ Suspended Sediment, Redistribution of Floodplain / Bank Material	Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology)
Off-Road Vehicle Use	Stream Riparian: ↑ Erosion, Sediment Load, △ Floodplain / Bank Composition Reservoir Riparian: ↑ Erosion, Sediment Load, △ Bank Morphology, Bank Composition	Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology) or Reservoir Morphometry[*2] & Bank Composition
Sand & Gravel Mining	Stream Riparian: ↑ Sediment Load, △ Stream Cross-Sectional Geometry, Entrenchment, Longitudinal Profile, Sinuosity, Channel Pattern / Location, Floodplain / Bank Composition	Stream Geomorphic Parameters[*1]
Altered Fire Regime	Stream Riparian: △ Sediment Load, Floodplain / Bank Composition Reservoir Riparian: △ Sediment Load, Bank Composition	Floodplain / Bank Composition

*1 Channel cross-section, width/depth, entrenchment, rates of bank erosion and downcutting/aggradation, longitudinal profile, sinuosity, channel pattern, channel location (lateral migration), and pebble count.

*2 Reservoir mean/maximum depth, volume/area, depth profile/bed slope.

Table 15. Stresses and impacts on riparian zone water quality / chemistry

Stresses	Effects	Indicators
Surface Water Diversions (from streams, reservoirs, or upstream tributaries to reservoirs)	Stream or Reservoir Riparian: ↑ Concentration of Nutrients, Suspended Sediment, & Other Dissolved and Suspended Constituents, Water Temperature	Nutrients*1, BOD/COD*2, DO Profile*3, Basic Water Quality Parameters*4, Temperature Profile [Palustrine Wetlands]
Groundwater Pumping	Stream or Reservoir Riparian: ↑ Concentration of Nutrients, Organic Carbon, & Suspended Solids, Water Temperature, △ Concentration of Other Dissolved & Suspended Constituents	Nutrients*1, BOD/COD*2, DO Profile*3, Basic Water Quality Parameters*4, Temperature Profile [Palustrine Wetlands]
Impoundments	Stream Riparian: ↓ and ↑ Suspended Sediment, Water Temperature	Suspended Sediment, Turbidity, Water Temperature [Palustrine Wetlands]
Shoreline Development (buildings & other structures)	Stream or Reservoir Riparian: ↑ Sediment Load, Water Temperature	Suspended Sediment, Basic Water Quality Parameters*4, Temperature Profile [Palustrine Wetlands]
Bank Stabilization / Channel Straightening	Stream or Reservoir Riparian: ↓ Sediment Load	Suspended Sediment, Turbidity [Palustrine Wetlands]
Bank Instability	Reservoir Riparian: ↑ Sediment Load	Suspended Sediment, Turbidity [Palustrine Wetlands]
Dredging / Filling (palustrine wetlands)	Stream or Reservoir Riparian: ↑ Suspended Sediment, Mobilization of Sorbed Contaminants, ↓ or ↑ Water Temperature / Gradient	Suspended Sediment, Turbidity, Potential Point Source Contaminants*5, BOD/COD*2, Temperature Profile [Palustrine Wetlands]

△ Infiltration / Runoff Rates (due to changes in upland or local land use – e.g., urbanization or agricultural development)	↓ or ↑ Sediment Load, Concentration of Other Dissolved & Suspended Constituents, Water Temperature	Suspended Sediment, Basic Water Quality Parameters*4, Temperature Profile [Palustrine Wetlands]
△ Sediment Load (due to changes in upland or local land use)	Stream or Reservoir Riparian: ↓ or ↑ Sediment Load	Suspended Sediment, Turbidity [Palustrine Wetlands]
Non-Point Nutrient & Organic Releases (upland or local land use)	Stream or Reservoir Riparian: ↑ Nutrients, Organic Carbon, Heavy Metals, Palustrine Wetland Eutrophication	Nutrients*1, BOD/COD*2, DO Profile*3, Basic Water Quality Parameters*4 [Palustrine Wetlands]
Permitted Wastewater Discharge to Streams	Stream Riparian: ↑ Nutrients, Organic Carbon, Heavy Metals, Aquatic Microorganisms, Palustrine Wetland Eutrophication	Aquatic Microorganisms*6, Nutrients*1, BOD/COD*2, DO Profile*3, Basic Water Quality Parameters*4 [Palustrine Wetlands]
Point Contaminant Releases (contaminated sites)	Stream or Reservoir Riparian: ↑ Synthetic Organic Compounds, Petroleum Hydrocarbons, Heavy Metals, Pesticides, Wastewater Contaminants, & Other Toxic Substances (as applicable)	Potential Point Source Contaminants*5, BOD/COD*2, Basic Water Quality Parameters*4 [Palustrine Wetlands]
Atmospheric Deposition	Stream or Reservoir Riparian: ↑ Nitrogen & Sulphur Compounds, Mercury & Other Metals, Pesticides (as applicable)	Nutrients*1, pH, Mercury & Other Metals, Pesticides (as applicable) Basic Water Quality Parameters*4 [Palustrine Wetlands]
Tamarisk	Stream or Reservoir Riparian: ↑ Salinity	Salinity [Palustrine Wetlands]
Other Exotic / Invasive Riparian Vegetation	Stream or Reservoir Riparian: ↓ or ↑ Bank Erosion, Sediment Load	Suspended Sediment, Turbidity [Palustrine Wetlands]

Removal of Upland Riparian Vegetation	Stream or Reservoir Riparian: ↓ Interception of Overland Flow, Cover, ↑ Nutrient Load, Sediment Load, Rate of Organic Carbon Input	Nutrients[*1], BOD/COD[*2], Suspended Sediment, Basic Water Quality Parameters[*4] [Palustrine Wetlands]
Flood	Stream or Reservoir Riparian: ↑ Concentration of Nutrients, Suspended Sediment, & Other Dissolved and Suspended Constituents, ↓ Water Temperature	Nutrients[*1], BOD/COD[*2], DO Profile[*3], Basic Water Quality Parameters[*4], Temperature Profile [Palustrine Wetlands]
Drought	Stream or Reservoir Riparian: ↑ Concentration of Nutrients, Suspended Sediment, & Other Dissolved and Suspended Constituents, Water Temperature	Nutrients[*1], BOD/COD[*2], DO Profile[*3], Basic Water Quality Parameters[*4], Temperature Profile [Palustrine Wetlands]
Climate Change (temperature, precipitation, wind)	Stream or Reservoir Riparian: ↓ or ↑ Concentration of Nutrients, Suspended Sediment, & Other Dissolved and Suspended Constituents, Water Temperature	Nutrients[*1], BOD/COD[*2], DO Profile[*3], Basic Water Quality Parameters[*4], Temperature Profile [Palustrine Wetlands]
Fragmentation (palustrine wetlands)	Loss of Patch Connectivity	Nutrients[*1], BOD/COD[*2], DO Profile[*3], Basic Water Quality Parameters[*4], Temperature Profile [Palustrine Wetlands]
Ungulate Grazing / Trampling	Stream or Reservoir Riparian: ↑ Aquatic Microorganisms, Sediment Load, Nutrient Load, Rate of Organic Carbon Input	Aquatic Microorganisms[*6], Nutrients[*1], BOD/COD[*2], DO Profile[*3], Basic Water Quality Parameters[*4] [Palustrine Wetlands]
Motorized Boating	↑ Suspended Sediment, Mobilization of Sorbed Contaminants, Petroleum Hydrocarbons	Suspended Sediment, Turbidity, Petroleum Hydrocarbons [Palustrine Wetlands]
Off-Road Vehicle Use	Stream or Reservoir Riparian: ↑ Erosion, Sediment Load	Suspended Sediment, Turbidity [Palustrine Wetlands]
Sand & Gravel Mining	Stream Riparian: ↑ Sediment Load	Suspended Sediment, Turbidity [Palustrine Wetlands]
Altered Fire Regime	Stream or Reservoir Riparian: ↓ or ↑ Nutrient Load, Sediment Load	Nutrients[*1], Suspended Sediment, Turbidity [Palustrine Wetlands]

*1 Nitrogen and phosphorous.

*2 Biological oxygen demand / chemical oxygen demand.

*3 Dissolved oxygen profile.

*4 Water temperature, pH, dissolved oxygen, major cations and anions, conductivity, turbidity.

*5 Synthetic organic compounds, gasoline & diesel-range organic compounds, metals, pesticides, & other toxic substances, as applicable.

*6 Bacteria, viruses, and protozoa.

Table 16. Stresses and impacts on riparian biota

Stresses	Effects	Indicators
Surface Water Diversions (from streams, reservoirs, or upstream tributaries to reservoirs)	↑ Concentration of Nutrients, Suspended Sediment, & Other Dissolved and Suspended Constituents, Water Temperature, Phytoplankton, Algae, Light Extinction, ↓ Riparian Water Table, Depth of Submergence (Palustrine Wetlands), △ Areal Extent / Location of Palustrine Wetlands	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates; Abundance of Phytoplankton & Algae (Palustrine Wetlands)
Groundwater Pumping	↑ Concentration of Nutrients, Organic Carbon, Suspended Solids, Water Temperature, Phytoplankton, Algae, Light Extinction, ↓ Riparian Water Table, Depth of Submergence (Palustrine Wetlands), △ Areal Extent / Location of Palustrine Wetlands	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates; Abundance of Phytoplankton & Algae (Palustrine Wetlands)
△ Local Stream Base Level(s)	↓ or ↑ Stream Stage, Riparian Water Table / Depth of Submergence (Palustrine Wetlands)	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Impoundments	Stream Riparian: ↓ and ↑ Suspended Sediment, Water Temperature, Light Extinction	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Shoreline Development (buildings & other structures)	Loss of Bank Habitat (Bank Modification), △ Water Quality, ↓ Amphibians, Waterfowl	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Bank Stabilization / Channel Straightening	Loss of Bank Vegetation / Habitat, ↓ Amphibians, Waterfowl	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates

Bank Instability	Loss of Bank Habitat	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Dredging / Filling (palustrine wetlands)	Loss / Alteration of Palustrine Wetland Habitat	Composition, Abundance, & Distribution of Palustrine Wetland Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
△ Infiltration / Runoff Rates (due to changes in upland or local land use – e.g., urbanization or agricultural development)	△ Streamflow / Reservoir Level, Riparian Water Table / Depth of Water in Palustrine Wetlands, Riparian Habitat, ↓ or ↑ Sediment Load, Concentration of Other Dissolved & Suspended Constituents, Water Temperature	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
△ Sediment Load (due to changes in upland or local land use)	↓ or ↑ Suspended Sediment, Deposition, △ Areal Extent / Location of Palustrine Wetlands, Light Extinction	Composition, Abundance, & Distribution of Palustrine Wetland Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Non-Point Nutrient & Organic Releases (upland or local land use)	↑ Nutrient Load, Rate of Organic Carbon Input, Heavy Metals, Phytoplankton, Algae, Light Extinction	Composition, Abundance, & Distribution of Palustrine Wetland Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates; Abundance of Phytoplankton & Algae (Palustrine Wetlands)
Permitted Wastewater Discharge to Streams	↑ Nutrient Load, Rate of Organic Carbon Input, Heavy Metals, Phytoplankton, Algae, Light Extinction	Composition, Abundance, & Distribution of Palustrine Wetland Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates; Abundance of Phytoplankton & Algae (Palustrine Wetlands)

Point Contaminant Releases (contaminated sites)	↑ Synthetic Organic Compounds, Petroleum Hydrocarbons, Heavy Metals, Pesticides, Wastewater Contaminants, & Other Toxic Substances (as applicable)	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Atmospheric Deposition	↑ Nitrogen & Sulphur Compounds, pH, Mercury & Other Metals, Pesticides (as applicable)	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Tamarisk	↑ Salinity	Tamarisk Abundance & Distribution; Composition, Abundance, & Distribution of Palustrine Wetland Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Other Exotic / Invasive Riparian Vegetation	Competition with Noninvasive Native Palustrine Wetland & Upland Riparian Vegetation, △ Riparian Habitat	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Clearing of Emergent Vegetation & Woody Debris	Loss of Riparian Habitat, ↓ Amphibians, Waterfowl, Fish Growth Rates, △ Water Quality	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Removal of Riparian Vegetation	↓ Interception of Overland Flow, Cover, ↑ Nutrient Load, Sediment Load, Rate of Organic Carbon Input, Loss of Riparian Habitat	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Exotic / Invasive Vertebrates & Invertebrates	Competition with Noninvasive Native Riparian Vertebrates & Invertebrates	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vertebrates & Invertebrates
Flood	△ Suspended Sediment, Water Quality, Water Temperature	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates

Drought	↓ Riparian Water Table / Depth of Water in Palustrine Wetlands, △ Water Quality, Water Temperature	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vertebrates & Invertebrates
Climate Change (temperature, precipitation, wind)	↓ or ↑ Air & Water Temperatures, Stream Stage / Reservoir Level, Riparian Water Table / Depth of Water in Palustrine Wetlands, Nutrient Load, Sediment Load, Concentrations of Other Dissolved & Suspended Constituents	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Fragmentation (palustrine wetlands)	Loss of Patch Connectivity (Palustrine Wetlands & Upland Riparian Habitat)	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Ungulate Grazing / Trampling	↑ Trampling of Riparian Vegetation & Banks, Nutrient Load, Sediment Load, Rate of Organic Carbon Input, Phytoplankton, Algae, Light Extinction	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates; Abundance of Phytoplankton & Algae (Palustrine Wetlands)
Off-Road Vehicle Use	↑ Bank Erosion, Sediment Load, Wetland Deposition, Light Extinction	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Sand & Gravel Mining (Stream)	Loss of Riparian Habitat	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Altered Fire Regime	↓ or ↑ Nutrient Load, Sediment Load, Rate of Organic Carbon Input, Phytoplankton, Algae, Light Extinction	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates; Abundance of Phytoplankton & Algae (Palustrine Wetlands)

Table 17. Summary of stresses and indicators of riparian ecosystem function and condition.

Stresses	Indicators
Surface Water Diversions (△ Streamflow)	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland; Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology); Nutrients[*2], BOD/COD[*3], DO Profile[*4], Basic Water Quality Parameters[*5], Temperature Profile [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates; Abundance of Phytoplankton & Algae (Palustrine Wetlands)
Groundwater Pumping (△ Baseflow, Streamflow)	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland; Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology); Nutrients[*2], BOD/COD[*3], DO Profile[*4], Basic Water Quality Parameters[*5], Temperature Profile [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates; Abundance of Phytoplankton & Algae (Palustrine Wetlands)
△ Local Stream Base Level(s)	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland; Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology); Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Impoundments	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland; Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology); Suspended Sediment, Turbidity, Water Temperature [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Shoreline Development (buildings & other structures)	Depth of Water in Palustrine Wetland; Stream Geomorphic Parameters[*1] (including Floodplain Morphology) <u>or</u> Reservoir Morphometry[*6]; Suspended Sediment, Basic Water Quality Parameters[*4]; Temperature Profile [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Bank Stabilization / Channel Straightening	Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology) <u>or</u> Reservoir Morphometry[*6] & Bank Composition; Suspended Sediment, Turbidity [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates

Bank Instability	Reservoir Morphometry*6 (Depth Profile/Bank Slope); Suspended Sediment, Turbidity [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Dredging / Filling (palustrine wetlands)	Stream Geomorphic Parameters*1 (including Floodplain Morphology) <u>or</u> Reservoir Morphometry*6; Suspended Sediment, Turbidity, Potential Point Source Contaminants*7, BOD/COD*3, Temperature Profile [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
△ Infiltration / Runoff Rates (due to changes in upland or local land use – e.g., urbanization or agricultural development)	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland; Stream Geomorphic Parameters*1 (including Bank & Floodplain Morphology); Suspended Sediment, Basic Water Quality Parameters*5, Temperature Profile [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
△ Sediment Load (due to changes in upland or local land use)	Stream Geomorphic Parameters*1 (including Bank & Floodplain Morphology) <u>or</u> Reservoir Morphometry*6 & Bed Composition; Suspended Sediment, Turbidity [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Non-Point Nutrient & Organic Releases (upland or local land use)	Nutrients*1, BOD/COD*2, DO Profile*3, Basic Water Quality Parameters*4 [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates; Abundance of Phytoplankton & Algae (Palustrine Wetlands)
Permitted Wastewater Discharge to Streams	Aquatic Microorganisms*6, Nutrients*1, BOD/COD*2, DO Profile*3, Basic Water Quality Parameters*4 [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates; Abundance of Phytoplankton & Algae (Palustrine Wetlands)
Point Contaminant Releases (contaminated sites)	Potential Point Source Contaminants*7, BOD/COD*3, Basic Water Quality Parameters*4 [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates

Atmospheric Deposition	Nutrients[*2], pH, Mercury & Other Metals, Pesticides (as applicable), Basic Water Quality Parameters[*4] [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Tamarisk	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland; Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology) or Reservoir Morphometry[*6]; Salinity [Palustrine Wetlands]; Tamarisk Abundance & Distribution; Composition, Abundance, & Distribution of Palustrine Wetland Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Other Exotic / Invasive Riparian Vegetation	Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology) or Reservoir Morphometry[*6];& Bank Composition; Suspended Sediment, Turbidity [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Clearing of Emergent Vegetation & Woody Debris	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Removal of Upland Riparian Vegetation	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland; Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology) or Reservoir Morphometry[*6] & Bank Composition; Nutrients[*1], BOD/COD[*2], Suspended Sediment, Basic Water Quality Parameters[*4] [Palustrine Wetlands]
Exotic / Invasive Vertebrates & Invertebrates	Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vertebrates & Invertebrates
Flood	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland; Stream Geomorphic Parameters[*1] (including Bank & Floodplain Morphology); Nutrients[*2], BOD/COD[*3], DO Profile[*4], Basic Water Quality Parameters[*5], Temperature Profile [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Drought	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland; Nutrients[*2], BOD/COD[*3], DO Profile[*4], Basic Water Quality Parameters[*5], Temperature Profile [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vertebrates & Invertebrates

Climate Change (temperature, precipitation, wind)	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland; Stream Geomorphic Parameters*1 (including Bank & Floodplain Morphology); Nutrients*2, BOD/COD*3, DO Profile*4, Basic Water Quality Parameters*5, Temperature Profile [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Fragmentation (including stream downcutting & floodplain / palustrine wetland abandonment)	Groundwater Level (Riparian Zone), Depth of Water in Palustrine Wetland; Nutrients*1, BOD/COD*2, DO Profile*3, Basic Water Quality Parameters*4, Temperature Profile [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Ungulate Grazing / Trampling	Stream Geomorphic Parameters*1 (including Bank & Floodplain Morphology) <u>or</u> Reservoir Morphometry*6 & Bank Composition; Aquatic Microorganisms*6, Nutrients*1, BOD/COD*2, DO Profile*3, Basic Water Quality Parameters*4 [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates; Abundance of Phytoplankton & Algae (Palustrine Wetlands)
Instream Driving / Vehicle Crossing	Suspended Sediment, Stream Geomorphic Parameters*1 (including Bank & Floodplain Morphology)
Motorized Boating	Suspended Sediment, Turbidity, Petroleum Hydrocarbons [Palustrine Wetlands]
Off-Road Vehicle Use	Suspended Sediment, Stream Geomorphic Parameters*1 <u>or</u> Reservoir Morphometry*6 & Bank Composition; Suspended Sediment, Turbidity [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Sand & Gravel Mining	Suspended Sediment, Stream Geomorphic Parameters*1; Suspended Sediment, Turbidity [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates
Altered Fire Regime	Suspended Sediment, Bank / Floodplain Composition; Nutrients*1, Suspended Sediment, Turbidity [Palustrine Wetlands]; Composition, Abundance, & Distribution of Palustrine Wetland / Upland Riparian Vegetation, Macroinvertebrates, Invertebrates, & Vertebrates; Abundance of Phytoplankton & Algae (Palustrine Wetlands)

*1 Channel cross-section, width/depth, entrenchment, rates of bank erosion and downcutting/aggradation, longitudinal profile, sinuosity, channel pattern, channel location (lateral migration), and pebble count.

*2 Nitrogen and phosphorous.

*3 Biological oxygen demand / chemical oxygen demand.

*4 Dissolved oxygen profile.

*5 Water temperature, pH, dissolved oxygen, major cations and anions, conductivity, turbidity.

*6 Reservoir mean/maximum depth, volume/area, depth profile/bed slope.

*7 Synthetic organic compounds, gasoline & diesel-range organic compounds, metals, pesticides, & other toxic substances, as applicable.

*8 Bacteria, viruses, and protozoa.

W.5. AQUATIC INVERTEBRATES AS INDICATORS OF ECOSYSTEM CONDITION

Macroinvertebrates are of central importance in aquatic ecosystems because of their variable roles as detritivores, herbivores, predators, competitors, and prey. In addition to their link with the biotic environment, macroinvertebrates are sensitive to the physical and chemical environment. Because macroinvertebrates are affected by water chemistry, they may be used to assess water quality indirectly in place of direct water chemistry analysis. Macroinvertebrates also show greater sensitivity to toxicity than other aquatic organisms (Rosenberg and Resh 1993). Certain taxa of invertebrate are more sensitive than others to specific chemicals. For example, plecopterans and baetids (Ephemeroptera) are very sensitive to insecticides, whereas other taxa are more sensitive to chemicals such as herbicides, fungicides, and industrial chemicals (Rosenberg and Resh 1993).

Because of their utility as an integrated indicator of water quality and the condition of aquatic ecosystems (Allan 1995, Karr and Chu 1999), aquatic macroinvertebrates have been identified as a key monitoring parameter (Miller et al. 2003). Benthic macroinvertebrates offer many advantages for monitoring watershed condition, including: (1) their presence in a variety of aquatic systems and habitats; (2) their occurrence as a large number of species which respond to a spectrum of environmental stressors due to varying habitat and water quality requirements; (3) their sedentary nature which facilitates analyses of the spatial distribution of pollutants and disturbance effects; and (4) their relatively long life-cycles, which elucidate temporal changes in environmental conditions (adapted from Rosenberg and Resh 1993). Invertebrate response to stressors and drivers can be rapid and provide an efficient means of examining temporal and spatial variations in aquatic ecosystem condition. Invertebrate monitoring should be conducted in conjunction with evaluations of aquatic and riparian habitat and water quality.

Adair, E.C., and D. Binkley. 2002. Co-limitation of first year Fremont cottonwood seedlings by nitrogen and water. *Wetlands* 22:425-429.

Albertson, F. W., and J. E. Weaver. 1945. Injury and death or recovery of trees in prairie climate. *Ecological Monographs* 15:395-433.

Allan, J.D. 1995. Stream Ecology: *Structure and Functioning of Running Waters*. Chapman and Hall, London. 388 p.

Allred, T.M., and J.C. Schmidt. 1999. Channel narrowing by vertical accretion along the Green River near Green River, Utah. *Geological Society of America Bulletin* 111:1757-1772.

Amaranthus, M., H. Jubas, and D. Arthur. 1989. Stream shading, summer streamflow and maximum water temperature following intense wildfire in headwater streams. Pages 75-91 *in* N.H. Berg (tech coord.), Proceedings of the symposium on fire and watershed management. USDA General Technical Report PSW-109.

Armitage, P.D., and G.E. Petts. 1992. Biotic score and prediction to assess the effects of water abstractions on river macroinvertebrates for conservation purposes. *Aquatic Conservation: Marine and Freshwater Ecosystems* 2:1-17.

Asner, G. P., S. Archer, R. F. Hughes, R. J. Ansley, and C. A. Wessman. 2003. Net changes in regional woody vegetation cover and carbon storage in Texas Drylands, 1937-1999. *Global Change Biology* 9:316-335.

Auble, G. T., and M. L. Scott. 1998. Fluvial disturbance patches and cottonwood recruitment along the upper Missouri River, Montana. *Wetlands* 18:546-556.

Auble, G.T., M.L. Scott, and J. M. Friedman. *In press*. Wetland and riparian vegetation along the Fremont River, Utah, to assess impacts of flow alteration on wetland and riparian area. *Wetlands* 00:00.

Bagstad, K.J., J.C. Stromberg, and S.J. Lite. *In press*. Response of herbaceous riparian plants to flooding of the San Pedro River, Arizona, USA. *Wetlands* 00:00.

Bain, M.B., J.T. Finn, and H.E. Booke. 1988. Streamflow regulation and fish community structure. *Ecology* 69:382-392.

Baker, W.L. 1990. Climate and hydrologic effects on the regeneration of Populus angustifolia James along the Animas River, Colorado. *Journal of Biogeography* 17:59-73.

Baltz, D.M., B. Vondracek, L.R. Brown, and P.B. Moyle. 1987. Influence of temperature on microhabitat choice by fishes in a California stream. *Transactions of the American Fisheries Society* 116:12-20.

Baltz, D.M., B. Vondracek, L.R. Brown, and P.B. Moyle. 1991. Seasonal changes in microhabitat selection by rainbow trout in a small stream. *Transactions of the American Fisheries Society* 120:166-176.

Barr, J. F. 1986. Population dynamics of Common Loon (Gavia immer) associated with mercury contamination in northwestern Ontario. Canadian Wildlife Service Occasional Paper 56. 23pp.

Beauchamp, V.B. 2004. Effects of flow regulation on a Sonoran riparian ecosystem, Verde River, Arizona. Ph.D. Dissertation, Arizona State University

Benavides-Solorio, J.D.D. 2003. Post-fire runoff and erosion at the plot and hillslope scale, Colorado Front Range. PhD Dissertation, Colorado State University.

Benbow, M.E., and R.W. Merritt. 2004. Road-salt toxicity of select Michigan wetland macroinvertebrates under different testing conditions. *Wetlands* 24:68-76.

Benda, L., N.L. Poff, D. Miller, T. Dunne, G. Reeves, G. Pess, and M. Pollock. 2004. The network dynamics hypothesis: how channel networks structure riverine habitats. *BioScience* 54:413-427.

Bendix, J. 1994. Scale, direction, and pattern in riparian vegetation-environment relationships. *Annals of the Association of American Geographers* 84:652-665.

Benenati, E.P., J.P. Shannon, and D.W. Blinn. 1998. Desiccation and recolonization of phytobenthos in a regulated desert river: Colorado River at Lees Ferry, Arizona, USA. *Regulated Rivers: Research & Management* 14:519-532.

Benenati, E.P., J.P. Shannon, D.W. Blinn, K.P. Wilson, and S.J. Hueftle. 2000. Reservoir-river linkages: Reservoir Powell and the Colorado River, Arizona. *Journal of the North American Benthological Society* 19:742-755.

Bickerton, M., G. Petts, P. Armitage, and E. Castella. 1993. Assessing the ecological effects of groundwater abstraction on chalk streams: 3 examples from Eastern England. *Regulated Rivers: Research & Management* 8:121-134.

Bennett, E., T. Reed-Anderson, J. Houser, J. Gabriel, and S. Carpenter. 1999. A phosphorus budget for the Lake Mendota watershed. Ecosystems 2:69-75.

Boening, D. 2000. Ecological effects, transport and fate of mercury: a general review. Chemosphere 40:1335-1351.

Blinn, D.W., J.P. Shannon, P.L. Benenati, and K.P. Wilson. 1998. Algal ecology in tailwater stream communities: the Colorado River below Glen Canyon Dam, Arizona. *Journal of Phycology* 34:734-740.

Boggs, K. and T. Weaver. 1994. Changes in vegetation and nutrient pools during riparian succession. *Wetlands* 14: 98-109.

Braatne, J.H., T.M. Hinckley, and R.F. Stettler. 1992. Influence of soil water on the physiological and morphological components of plant water balance in *Populus trichocarpa, Populus deltoides* and their F1 hybrids. *Tree Physiology* 11:325-339.

Bradford, K.J., and T.C. Hsiao. 1982. Physiological responses to moderate water stress. Pages 264-324 *in* O.L. Lang, P.S. Nobel, C.B. Osmond, and H. Ziegler, (eds.), *Encyclopedia of Plant Physiology*. Vol. 12B. Springer-Verlag, Vienna, Austria.

Brady, N.C. 1974. The Nature and Properties of Soils. Eighth edition. MacMillan Publishing Co. Inc., New York, New York. 639 p.

Bramblett, R. G., and K. D. Fausch. 1991a. Fishes, macroinvertebrates and aquatic habitats of the Purgatoire River in Piñon Canyon, Colorado. Southwestern Naturalist. 36:281-294.

Bramblett, R. G., and K. D. Fausch. 1991b. Variable fish communities and the index of biotic integrity in a western Great Plains river. Transactions of the American Fish Society. 120:752-769.

Bravard, J., C. Amoros, G. Pautou, G. Bornette, M. Bournaud, M. Creuzé Des Châtelliers, J. Gibert, J. Peiry, J. Perrin, and H. Tachet. 1997. River incision in south-east France: morphological phenomena and ecological effects. *Regulated Rivers* 13:75-90.

Breshears, D.D., and C.D. Allen. 2002. The importance of rapid, disturbance-induced losses in carbon management and sequestration. *Global Ecology & Biogeography* 11:1-5.

Breshears, D.D., J.J. Whicker, M.P. Johansen, and J.E. Pinder, III. 2003. Wind and water erosion and transport in semi-arid shrubland, grassland and forest ecosystems: Quantifying dominance of horizontal wind-driven transport. *Earth Surface Processes and Landforms* 28: 1189-1209.

Briers, R.A., J.H.R.Gee, and R. Geoghegan. 2004. Effects of the North Atlantic Oscillation on growth and phenology of stream insects. *Ecography* 27:811-817.

Brinson, M.M., B.L. Swift, R.C. Plantico, and J.S. Barclay. 1981. Riparian ecosystems: their ecology and status. U.S. Fish and Wildlife Service Biological Report 81. 155 p.

Brown, L. R. 2000. Fish communities and their associations with environmental variables, lower San Joaquin River drainage, CA. *Environmental Biology of Fishes* 57:251-269.

Brown, L.R., and T. Ford. 2002. Effects of flow on the fish communities of a regulated California river: implications for managing native fishes. *River Research and Application* 18:331-342.

Bunn, S.E., and A.H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* 30:492-507.

Burkham, D.E. 1972. Channel changes of the Gila River in Safford Valley, Arizona 1846-1970. U.S. Geological Survey Professional Paper 655-G.

Busch, D.E., N.L. Ingraham, and S.D. Smith. 1992. Water uptake in woody riparian phreatophytes of the southeastern United States: a stable isotope study. *Ecological Applications* 2:450-459.

Busch, D.E., and S.D. Smith. 1995. Mechanisms associated with decline of woody species in riparian ecosystems of the southwestern U.S. *Ecological Monographs* 65:347-370.

Cairns, J. Jr., and J.R. Pratt. 1993. A history of biological monitoring using benthic macroinvertebrates. Pages 10-27 *in* D.M. Rosenberg and V.H. Resh (eds.), *Freshwater biomonitoring and benthic macroinvertebrates*. Chapman & Hall, New York, New York.
Canton, S.P., L.D. Cline, R.A. Short, and J.V. Ward. 1984. The macroinvertebrates and fish of a Colorado stream during a period of fluctuating discharge. *Freshwater Biology* 14:311-316.
Carothers, S.W. and S.W. Aitchinson. 1976. An ecological survey of the riparian zone of the Colorado River between Lee's Ferry and the Grand Wash Cliffs, Arizona. Colorado River Research Series Technical Report No. 10, Grand Canyon National Park, Arizona.
Carsten von der Ohe, P., and M. Liess. 2004. Relative sensitivity distribution of aquatic invertebrates to organic and metal compounds. *Environmental Toxicology and Chemistry* 23:150-156.
Castella, E., M. Bickerton, P.D. Armitage, and G.E. Petts. 1995. The effects of water abstractions on invertebrate communities in U.K. streams. *Hydrobiologia* 308:167-182.
Carpenter S. and D. Lodge. 1986. Effects of submersed macrophytes on ecosystem processes. Aquatic Botany 26:341-370.
Carpenter, S., D. Bolgrien, R. Lathrop, C. Stow, T. Reed, and M. Wilson. 1998. Ecological and economic analysis of lake eutrophication by nonpoint pollution. Australian Journal of Ecology. 1:68-79.
Cayan, D.R., K.T. Redmond, and L.G. Riddle. 1999. ENSO and hydrologic extremes in the western United States. *Journal of Climate* 12:2881-2893.
Chapin, F.S., III. 1993. Funtional role of growth forms in ecosystem and global processes. Pages 287-312 *in* J.R. Ehleringer and C.B. Field (eds.), *Scaling physiological processes: leaf to globe*. Academic Press, San Diego, California.
Chapin, D.M., R.L. Beschta, and H.W. Shen. 2002. Relationships between flood frequencies and riparian plant communities in the Upper Klamath Basin, Oregon. *Journal of the American Waters Resources Association* 38:603-617.
Chapin, F.S., III, M.S. Torn, and M. Tateno. 1996. Principles of ecosystem sustainability. *The American Naturalist* 148:1016-1037.
Cipra, J.E., E.F. Kelly, L. McDonald and J. Norman. 2002. Soil properties, erosion, and implications for rehabilitation and aquatic systems. Pages 204-219 *in* R. Graham (ed.), Hayman Fire Case Study. USDA Forest Service General Technical Report, RM-141.
Cleverly, J.R., S.D. Smith, A. Sala, and D.A. Devitt. 1997. Invasive capacity of *Tamarix ramosissima* in a Mojave Desert floodplain: the role of drought *Oecologia* 111:12-18.
Cole, G. 1994. A Textbook of Limnology, Fourth Edition. Waveland Press. 412 pp.
Comstock, J.P., and J.R. Ehleringer. 1992. Plant adaptation in the Great Basin and Colorado Plateau. *The Great Basin Naturalist* 52:195-215.
Connell, J.H. 1978. Diversity in tropical rain forests and coral reefs: high diversity of trees and corals is maintained only in a non-equilibrium state. *Science* 199:1302-1310.
Cook, R.U., and R.W. Reeves. 1976. *Arroyos and environmental change in the American southwest.* Clarendon Press, Oxford, England. 213 p.
Cooper, D.J., D.M. Merritt, D.C. Anderson, and R.A. Chimner. 1999. Factors controlling the establishment of Fremont cottonwood seedlings on the upper Green River, USA. *Regulated Rivers: Research and Management* 15:419-440.
Cooper, D.J., D.R. D'Amico, and M.L. Scott. 2003. Physiological and morphological response patterns of Populus deltoides to alluvial groundwater declines. *Environmental Management* 31:215-226.
Covich, A.P., M.A. Palmer, and T.A. Crowl. 1999. The role of benthic invertebrate species in freshwater ecosystems. *BioScience* 49:119-127.
Cowardin, L.M., V. Carter, F.C. Golet, and E.T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. U.S. Fish and Wildlife Service. FWS/OBS-79/31. Northern Prairie Wildlife Research Center Online. http://www.npwrc.usgs.gov/resource/1998/classwet/classwet.htm (Version 04DEC98).

Cross, F. B., R. E. Moss, and J. T. Collins. 1985. Assessment of dewatering impacts on stream fisheries in the Arkansas and Cimarron rivers. Report to Kansas Department of Wildlife and Parks, Contract No. 46, Pratt, KS.

Cross, F. B., and R. E. Moss. 1987. Historic changes in fish communities and aquatic habitats in plains streams of Kansas. Pp. 155-165 in W. J. Matthews and D. C Heins, eds. Communitiy and evolutionary ecology of North American stream fishes. University of Oklahoma Press, Norman.

Cuffney, T.F., M.R. Meador, S.D. Porter, and M.E. Gurtz. 1997. Distribution of fish, benthic invertebrate, and algal communities in relation to physical and chemical conditions, Yakima River Basin, Washington, 1990. U.S. Geological Survey Water Resources Investigations Report 96-4280. 94 p.

Dahl, T.E. 2000. Status and trends of wetlands in the conterminous United States 1986 to 1997. U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C. 82 pp.

Dahm, C.N., M.A. Baker, D.I. Moore, and J.R. Thibault. 2003. Coupled biogeochemical and hydrological responses of streams and rivers to drought. *Freshwater Biology* 48:1219-1231.

Dale, V.H., S. Brown, R.A. Haeuber, N.T. Hobbs, N. Huntly, R.J. Naiman, W.E. Riebsame, M.G. Turner, and T.J. Valone. 2000. Ecological principles and guidelines for managing the use of land. *Ecological Applications* 10:639-670.

Davies-Colley, R.J., J.W. Nagels, R.A. Smith, R.G. Young, and C.J. Phillips. 2004. Water quality impact of a dairy cow herd crossing a stream. *New Zealand Journal of Marine and Freshwater Research* 38:569-576.

Davis, M. B. 1981. Quaternary history and the stability of forest communities. In D.C. West, H. Shigart and D. Botkin, editors, Forest Succession. Springer Verlag.

DeAngelis, D., J. Kitchell, and W. Post. 1985. The influence of naticid predation on evolutionary strategy of bivalve prey: conclusions from a model. American Naturalist 126:817-842.

Dennis, N. 1989. The effects of fire on watersheds: a summary. Pages 92-95 *in* N.H. Berg (tech coord.), Proceedings of the symposium on fire and watershed management. USDA General Technical Report PSW-109.

Diamond, J.M., and V.B. Serveiss. 2001. Identifying sources of stress to native aquatic fauna using a watershed ecological risk assessment framework. *Environmental Science and Technology* 35:4711-4718.

Díaz, S., and M. Cabido. 2001. Vive la différence: plant functional diversity matters to ecosystem processes. *Trends in Ecology & Evolution* 16:646-655.

Dillon, P. and L. Molot 1997. Effect of landscape form on export of DOC, iron and phosphorus from forested stream catchments. Water Resources Res. 33:25912600.

Dobkin, D. S., A. C. Rich, and W. H. Pyle. 1998. Habitat and avifaunal recovery from livestock grazing in a riparian meadow system of the northwestern Great Basin. *Conservation Biology* 12:209-221.

Dugan, J. T., T. McGrath, and R. B. Zelt. 1994. Water-level changes in the High Plains aquifer predevelopment to 1992. U.S. Geological Survey Water-Resources Investigations Report 94-4027. 34 pp.

Earl, S.R., and D.W. Blinn. 2003. Effects of wildfire ash on water chemistry and biota in South-Western U.S.A. streams. *Freshwater Biology* 48:1015-1030.

Ehleringer, J.R., S. Schwinning, and R. Gebauer. 2000. Water use in arid land ecosystems. Pages 347-365 *in* M.C. Press, J.D. Scholes, and M.G. Barker (eds.), Physiological Plant Ecology. Proceedings of the 39th Symposium of the British Ecological Society, 7-9 September 1998, University of York. Blackwell Science, Boston, Massachusettes.

Ellison, L., and E.J. Woolfolk. 1937. Effects of drought on vegetation near Miles City, Montana. *Ecology* 18:329-336.

Engel, S. 1990. Ecosystem responses to growth and control of submersed macrophytes: a literature review. Tech. Bull. 170. Department of Natural Resources, Madison, WI, USA.

Erman, N.A., and D.C. Erman. 1995. Spring permanence, Trichoptera species richness, and the role of drought. *Journal of the Kansas Entomological Society* 68:50-64.

Eschner, T. R., R. F. Hadley, and K. D. Crowley. 1983. Hydrologic and morphologic changes in channels of the Platte River basin in Colorado, Wyoming, and Nebraska: a historical perspective. Geological Survey Professional Paper 1277-A, Washington DC.
Everitt, B.L. 1968. Use of the cottonwood in an investigation of the recent history of a floodplain. *American Journal of Science* 266:417-439.
Everitt, B.L. 1980. Ecology of saltcedar: a plea for research. *Environmental Geology* 3:77-84.
Fausch, K. D. and K. R. Bestgen. 1997. Ecology of fishes indigenous to the central and southwestern Great Plains. Knopf, F. L. and Samson, F. B., Editors. Ecology and conservation of Great Plains vertebrates. New York: Springer; 1997; pp. 131-166.
Fausch, K. D. and R. G. Bramblett. 1991. Disturbance and fish communities in intermittent tributaries of a western Great Plains river. Copeia. 1991:659-674.
Feminella, J.W., and C.P. Hawkins. 1995. Interactions between stream herbivores and periphyton: a quantitative analysis of past experiments. *Journal of the North American Benthological Society* 14:465-509.
Fisher, S. G. 1983. Succession in streams. Pages 7-27 *in* J.R. Barnes and G.W. Minshall (eds.), *Stream Ecology: application and testing of a general ecological theory*. Plenum Press, New York.
Flug, M. 1998. Ecosystem Resource Considerations in Reservoir Management: Water Resources Update: Universities Council on Water Resources. 43-56.
Freckman, D.W., T.H. Blackburn, L. Brussaard, P. Hutchings, M.A. Palmer, and P.V.R. Snelgrove. 1997. Linking biodiversity and ecosystem functioning of soils and sediments. *Ambio* 26:556-562.
Friedman, J.M., G.T. Auble, P.B. Shafroth, M.L. Scott, M.F. Merligiano, M.D. Freehling, and E.R. Griffin. *In press.* Dominance of non-native riparian trees in western USA. *Biological Invasions* 00:00.
Friedman, J.M., and V.J. Lee. 2002. Extreme floods, channel change, and riparian forests along ephemeral streams. *Ecology* 72:409-425.
Friedman, J.M., W.R. Osterkamp, and W.M. Lewis, Jr. 1996. Channel narrowing and vegetation development following a Great Plains flood. *Ecology* 77:2167-2181.
Frissell, C.A., W.J. Liss, C.E. Warren and M.D. Hurley. 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. *Environmental Management* 10:199-214.
Frost, T., D. Angelis, S. Bartell, D. Hall, and S. Hurlbert. 1988. Scale in the design and interpretation of aquatic communities research. In S. R. Carpenter, Complex interactions in lake communities. Springer Verlag.
Garrison, P. and R. Wakeman. 2000. Use of paleolimnolgy to document lake shoreland development effect on water quality. Journal of Paleolimnology 4:369-393.
Glass, G. 2001. Methylmercury bioaccumulation dependence on northern pike age and size in 20 Minnesota lakes. In R. Lipinsky, J. Hermens, K. Jones, and D. Muir, editors, Persistent, bioaccumulation and toxic chemicals. I. Fate and exposure. Washington, DC, USA. ACS Symposium Series 772:150-163.
Gordon, N.D., T.A. McHahon, B.L. Finlayson. 1992. Stream hydrology: an introduction for ecologists. John Wiley and Sons Inc., New York, New York.
Graf, W.L. 1978. Fluvial adjustments to the spread of tamarisk in the Colorado Plateau Region. *Geological Society of America Bulletin* 89:1491-1501.
Graf, W. L. 1999. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research* 35(4):1305-1311.
Grams, P.E. and J.C. Schmidt. 2002. Geomorphology of the Green River in the Eastern Uinta Mountains, Dinosaur National Monument, Colorado and Utah. Pages 81-111 *in* A.J. Miler and A. Gupta (eds.), *Varieties of Fluvial Form*, John Wiley & Sons, Oxford, England.
Gray, L. J. and W. K. Dodd. 1998. Structure and dynamics of aquatic communities. Knapp, A. K.; Briggs, J. M.; Hartnett, D. C., and Collins, S. L., editors. Grassland dynamics: long-term ecological research in tallgrass prairie. New York, NY: Oxford University Press. pp. 177-189.

Gray, L. J.; G. L. Macpherson, J. K. Koeliker, and W. K. Dodds. 1998. Hydrology and aquatic chemistry. Knapp, A. K.; Briggs, J. M.; Hartnett, D. C., and Collins, S. L., editors. Grassland dynamics: long-term ecological research in tallgrass prairie. New York, NY: Oxford University Press. pp. 159-176.

Gregory, H.E. 1916. The Navajo country. U.S. Geological Survey Water-Supply Paper 380. Washington Government Printing Office. Washington, D.C.

Gregory, S.V., F. J. Swanson, W. A. McKee, and K. W. Cummins. 1991. An ecosystem perspective of riparian zones: focus on links between land and water. *BioScience* 41:540-550.

Groeneveld, D.P., and T.E. Griepentrog. 1985. Interdependence of groundwater, riparian vegetation, and streambank stability: a case study. USDA Forest Service General Technical Report RM 120:44-48.

Haefner, J.W., and A.M. Lindahl. 1988. The ecology of small pools in Capitol Reef National Park, Utah. Final Report for Phase I of: USDI/NPS Contract No. PX-1350-7-0259. 25 p.

Haefner, J.W., and A.M. Lindahl. 1991. The ecology of small pools in Capitol Reef National Park, UT: Phase II. Final Report for Phase II of USDI/NPS Contract No. PX-1350-8-0187. 172 p.

Hereford, R. 1984. Climate and ephemeral-stream processes: twentieth-century geomorphology and alluvial stratigraphy of the Little Colorado River, Arizona. *Geological Society of America Bulletin* 95:654-668.

Hereford, R. 1986. Modern alluvial history of the Paria River drainage basin, southern Utah. *Quaternary Research* 25:293-311.

Hereford, R. 1987. Late Holocene sediment storage in canyons of the Colorado Plateau. Geological Society of America Bulletin 99:261-271.

Hereford, R., and R.H. Webb. 1992. Historic variation of warm-season rainfall, southern Colorado Plateau, Southwestern USA. *Climatic Change* 22:239-256.

Hereford, R., R. H. Webb, and S. Graham. 2002. Precipitation history of the Colorado Plateau Region, 1900-2000. USGS Fact Sheet 119-02. U.S. Department of Interior, U.S. Geological Survey. 4 p.

Horton, J.L., T.E. Kolb, and S.C. Hart. 2001a. Physiological response to groundwater depth varies among species and with river flow regulation. *Ecological Applications* 11:1046-1059.

Horton, J.L., T.E. Kolb, and S.C. Hart. 2001b. Responses of riparian trees to interannual variation in ground water depth in a semi-arid river basin. *Plant, Cell and Environment* 24:293-304.

Huntzinger, T. L. 1996. Surface water: a critical Great Plains resource. In S. Johnson and A. Bouzaher, editors. Conservation of Great Plains ecosystems: current science, future options. Kluwer Academic Press, Dordrecht, The Netherlands.

Huston, M. 1979. A general hypothesis of species diversity. *American Naturalist* 113:81-101.

Hutchinson, G.E. 1961. The paradox of the plankton. *American Naturalist* 95:137-145.

Hutchinson, G.E. 1969. Eutrophication, past and present. In Eutrophication: Causes, consequences and corrections. National Academy of Sciences, Washington, DC, USA.

Hynes, H.B.N. 1975. The stream and its valley. *Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie* 19:1-15.

Innis, S.A., R.J. Naiman, and S.R. Elliott. 2000. Indicators and assessment methods for measuring the ecological integrity of semi-aquatic terrestrial environments. *Hydrobiologica* 422/423: 111-131.

Jenny, H. 1941. *Factors of soil formation: a system of quantitative pedology*. McGraw-Hill, New York, New York. 281 p.

Jenny, H. 1980. Th*e soil resource: origin and behavior.* Springer-Verlag, New York, New York. 377 p.

Johnson, L. 2001. Overland dispersal of aquatic invasive species: a risk assessment of transient recreational boating. Ecological Applications 11:1789-1792.

Johnson, R.K., T. Wiederholm, and D.M. Rosenberg. 1993. Freshwater biomonitoring using individual organisms, populations, and species assemblages of benthic macroinvertebrates.

Pages 40-158 *in* D.M. Rosenberg and V.H. Resh (eds.), *Freshwater biomonitoring and benthic macroinvertebrates*. Chapman & Hall, New York, New York, USA.
Jordan, D. S. 1891. Report on explorations in Colorado and Utah during the summer 1889, with an account of fishes found in each of the river basins examined. U. S. Fisheries Commission Bulletin 9:1-40.
Kallemeyn, L. 1987. Correlation of regulated lake levels and climatic factors with abundance of young-of-the-year walleye and yellow perch in four lakes in Voyageurs National Park. North American Journal of Fisheries Management 7:513-521.
Kaller, M.D., and K.J. Hartman. 2004. Evidence of a threshold level of fine sediment accumulation for altering benthic macroinvertebrate communities. *Hydrobiologia* 518:95-104.
Karasov, W. and M. Meyer. 2000. Testing the role of contaminants in depressing avian numbers. Revista Chilena de Hisstoria Natural. 73:461-471.
Karr, J.R. 1991. Biological integrity: a long-neglected aspect of water resource management. *Ecological Applications* 1:66-84.
Karr, J.R., and E.W. Chu. 1999. *Restoring life in running waters*. Island Press, Washington, D.C. 206 p.
Kauffman, J. B., and W. C. Krueger. 1984. Livestock impacts on riparian ecosystems and streamside management implications: a review. *Journal of Range Management* 37:430-438.
Kaylor, J.F., C.C. Starring, and C.P. Ditman. 1935. A survey of past plantings. Pages 39-47 *in* Possibilities of shelterbelt planting in the Plains region. U.S. Forest Service, Washington, D.C.
Kemp, W., M. Brooks, and R. Hood. 2001. Nutrient enrichment, habitat variability and trophic transfer efficiency in simple models of pelagic ecosystems. Marine Ecological Progress Series 223:73-87.
Klump, V., D. Edgington. P. Sager, and D. Robertson. 1996. Sediment phosphorus cycling and a phosphorus mass balance for the Green Bay (Lake Michigan) ecosystem. Can. J. Fish. Aquat. Sci. 54:10-27.
Knopf, F. L., and M. L. Scott. 1990. Altered flows and created landscapes in the Platte River headwaters, 1840-1990. Pages 47-70 in J. M. Sweeney, editor. Management of dynamic ecosystems. North Central Section of the Wildlife Society, West Lafayette, Ind.
Kondolf, G.M. 1994. Geomorphic and environmental effects of instream gravel mining. *Landscape and Urban Planning* 28:225-243.
Kondolf, G.M. 1997. Hungry water: effects of dams and gravel mining on river channels. *Environmental Management* 21:533-551.
Kondolf, G.M., and R.R. Curry. 1986. Channel erosion along the Carmel River, Monterey County, California. *Earth Surface Processes and Landforms* 11:307-319.
Koplin, D. W., M. R. Burkart, and E. M. Thurman. 1994. Herbicides and nitrate in near-surface aquifers in the midcontinental United States, 1991. U.S. Geological Survey Water-Supply Paper 2413. 34 pp.
Kraft, C., P. Sullivan, A. Karatayev, L. Burlakova, J. Nekola, L Johnson and D. Padilla. 2002. Landscape patterns of an aquatic invader: assessing dispersal from spatial distributions. Ecological Applications 12:749-759.
Kromm, D.E., and S.E. White. 1992. Groundwater Exploitation in the High Plains. University Press of Kansas, Lawrence, Kansas, USA.
Landres, P., S. Meyer, and S. Mathews. 2001. The wilderness act and fish stocking: an overview of legislation, judicial interpretation and agency implementation. Ecosystems 4:287-295.
Lane, P.N., and G.J. Sheridan. 2002. Impact of an unsealed forest road stream crossing: water quality and sediment sources. *Hydrological Processes* 16:2599-2612.
Lavelle, P. 1997. Faunal activities and soil processes: adaptive strategies that determine ecosystem function. *Advances in Ecological Research* 27:93-132.
Leland, H.V., and S.V. Fend. 1998. Benthic invertebrate distributions in the San Joaquin River, California, in relation to physical and chemical factors. *Canadian Journal of Fisheries and Aquatic Sciences* 55:1051-1067.
Leopold, L.B. 1994. *A View of the River*. Harvard Univeristy Press, Cambridge, Massachusetts.

Lenat, D.R. 1984. Agriculture and stream water quality: a biological evaluation of erosion control practices. *Environmental Management* 8:333-344.

Lodge, D. and J. Lorman. 1987. Reduction in submersed macrophyte biomass and species richness by the crayfish, Orconectes rusticus. Can J. Fish. Aquat. Sci. 44:591-597.

Lohr, S. C., and K. D. Fausch. 1997. Multiscale analysis of natural variability in stream fish assemblages of a western Great Plains watershed. *Copeia* 4:706-724.

Longo, P. J., and D. W. Yoskowitz. 2002. Water on the Great Plains: issues and policies. Texas Tech U., Lubbock. 200pp.

Ludwig, J.A., and D.J. Tongway. 1997. A landscape approach to rangeland ecology. Pages 1-12 *in* J. Ludwig, D. Tongway, D. Freudenberger, J. Noble, and K. Hodgkinson (eds.), *Landscape ecology, function and management: principles from Australia's rangelands*. CSIRO Publishing, Collingwood, VIC, Australia.

Lyons, J. 1996. Patterns in the species composition of fish assemblages among Wisconsin streams. *Environmental Biology of Fishes* 45:329-341.

Mackay, D. and L. Toose. 2003. Quantifying the fate of mercury in the Greal Lakes basin: Towards an ecosystem approach. Unpubl. Report. Canadian Env. Modelling Centre, Trent University, Peterborough, ON, CN.

Mahoney, J.B., and S.B. Rood. 1992. Response of hybrid poplar to water table decline in different substrates. *Forest Ecology and Management* 54:141-156.

Mahoney, J.M., and S.B. Rood. 1998. Streamflow requirements for cottonwood seedling recruitment—an integrative model. *Wetlands* 18:634-645.

Mantua, N.J., and S.R. Hare. 2002. The Pacific decadal oscillation. *Journal of Oceanography* 58: 35-42.

Maret, T.R. 1995. Water-quality assessment of the Upper Snake River Basin, Idaho and Western Wyoming-summary of aquatic biological data for surface water through 1992. U.S. Geological Survey Water-Resources Investigations Report 95-4006. 59 p.

Maret, T. R., C. T. Robinson, and G. W. Minshall. 1997. Fish assemblages and environmental correlates in least-disturbed streams of the Upper Snake River basin. *Transactions of the American Fisheries Society* 126:200-216.

Matta, M.B., C. Cairncross, and R.M. Kocan. 1998. Possible effects of polychlorinated biphenyls on sex determination in rainbow trout. *Environmental Toxicology and Chemistry* 17:26-29.

Matthews, W. J. and E. G. Zimmermann. 1990. Potential effects of global warming on native fishes of the southern Great Plains and the southwest. Fisheries. 15(6):26-32.

McBride, J.B., and J. Strahan. 1984. Establishment and survival of woody riparian species on gravel bars of an intermittent stream. *American Midland Naturalist* 112:235-245.

McCafferty, W.P. 1998. *Aquatic entomology: the fishermen's and ecologists' illustrated guide to insects and their relatives.* Jones and Bartlett Publishers, Sudbury, Massachusetts, USA. 448 p.

McDowall, R.M. 2003. Impacts of introduced salmonids on native galaxiids in New Zealand upland streams: a new look at an old problem. *Transactions of the American Fisheries Society* 132:229-238.

McMahon, R. 2002. Evolutionary and physiological adaptation of aquatic invasive animals: r-selection vs resistance. Can. J. Fish. Aquat. Sci. 59:1235-1244.

Meador, M.R., L.R. Brown, and T. Short. 2003. Relations between introduced fish and environmental conditions at large geographic scales. *Ecological Indicators* 3:81-92.

Mead, J. R. 1896. A dying river. Transactions of the Kansas Academy of Sciences. 14:111-112.

Meadows, D.W. 2001. Effects of bison trampling on stream macroinvertebrate community structure on Antelope Island, Utah. *Journal of Freshwater Ecology* 16:83-92.

Meffe, G.K. 1984. Effects of abiotic disturbance on coexistence of predator and prey fish species. *Ecology* 65:1525-1534.

Meinzer, O.E. 1927. Plants as indicators of ground water. U.S. Geological Survey Water-Supply paper 577. 95 p.

Minckley, W.L., and J.E. Deacon. 1968. Southwestern fishes and the enigma of “endangered species.” *Science* 159:1424-1432.
Millard, S. and P. Sager. 1994. Comparison of phosphorus, light climate and photosynthesis between two culturally eutrophic bays: Green Bay, Lake Michigan and Bay of Quinte, Lake Ontario. Can. J. Fish, Aquat. Sci. 51:2579-2590.
Miller, M. E., D. Sharrow, and L. Cudlip. 2003. Northern Colorado Plateau Vital Signs Network and Prototype Cluster plan for natural resources monitoring: Phase II report. National Park Service, Northern Colorado Plateau Network, Moab, UT. 111 p + appendices.
Mitsch, W.J., and J.G. Gosselink. 1993. *Wetlands*. Second edition. Van Nostrand Reinhold, New York, New York.
Mitsch, W.J., and J.G. Gosselink. 2000. *Wetlands*. Third edition. John Wiley & Sons, New York, New York.
Montogomery, D.R. 1999. Process domains and the river continuum. *Journal of the American Water Resources Association* 35:397-410.
Montgomery, D.R. and J.M. Buffington. 1997. Channel reach morphology in mountain drainage basins. *Geological Society of America Bulletin*. 109: 596-611.
Montgomery, D.R. and L.H. MacDonald. 2002. Diagnostic approach to stream channel assessment and monitoring. *Journal of the American Water Resources Association* 38: 1-16.
Moody, J.A. and D.A. Martin. 2001. Hydrologic and sedimentologic response of two burned watershed in Colorado. US Geological Survey Water-Resources Investigation Report. WRIR 01-4122.
Munn, M.D., R.W. Black, and S.J. Gruber. 2002. Response of benthic algae to environmental gradients in an agriculturally dominated landscape. *Journal of the North American Benthological Society* 21:221-237.
Nadler, C. T., and S. A. Schumm. 1981. Metamorphosis of South Platte and Arkansas Rivers, eastern Colorado. Physiological Geography. 2:95-115.
Naiman, R.J., H. Decamps, J. Pastor, and C.A. Johnston. 1988. The potential importance of boundaries to fluvial ecosystems. *Journal of the North American Benthological Society* 7:289-306.
Naiman, R.J., D.G. Lonzarich, T.J. Beechie, and S.C. Ralph. 1992. General principles of classification and the assessment of conservation potential in rivers. Pages 93-123 *in* P.J. Boon, P. Calow, and G.E. Petts (eds.), *River Conservation and Management*. John Wiley and Sons, New York, New York.
Nilsson, C., A. Ekblad, M. Gardfjell, and B. Carlberg. 1991. Long-term effects of river regulation on river margin vegetation. *Journal of Applied Ecology* 28:963-987.
Noon, B.R. 2003. Conceptual issues in monitoring ecological systems. Pages 27-71 *in* D.E. Busch and J.C. Trexler (eds.). *Monitoring ecosystems: Interdisciplinary approaches for evaluating ecoregional initiatives.* Island Press, Washington, D.C.
Norman, J. and P. Sager 1978. Modeling phosphorus transfer rates in lake water. J. Theoretical Biology 71:381-385.
Noy-Meir, I. 1973. Desert ecosystems: Environment and producers. *Annual Review of Ecology and Systematics* 4:25-51.
Olden, J.D. and N.L. Poff. 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications* 19: 101-121.
Ohmart, R.D., and B.W. Anderson. 1982. North American desert riparian ecosystems. Pages 433-479 *in* G.L. Bender (ed.), *Reference Handbook on the Deserts of North America*, Greenwood Press, Westport, CN.
Pallardy, S.G., J.S. Pereia, and W.C. Parker. 1991. Measuring the state of water in tree systems. Pages 28-75 *in* J.P. Lassie, and T.M. Hinckley (eds.), *Techniques and Approaches in Forest Tree Ecophysiology.* CRC Press Inc., Boca Raton, Florida.
Petts, G.E. 1987. Time-scales for ecological change in regulated rivers. Pages 257-266, *in* J.F. Crain and J.B. Kemper (eds.), *Regulated Streams*, Plenum Press, New York, New York, USA.

Platts, W.S. 1991. Livestock grazing. Pages 389-423 *in* W.R. Meehan (ed.), *Influences of Forest and Rangeland management on Salmonid Fishes and Their Habitats,* American Fisheries Society Special Publication 19, Bethesda, MD, USA.

Poff, N.L., J.D. Allen, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. *BioScience* 47:769-784.

Poff, N.L. and J.V. Ward. 1989. Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patters. *Canadian Journal of Fisheries and Aquatic Sciences* 46:1805-1817.

Power, M. 1990. Effects of fish in river food webs. *Science* 250:811-814.

Power, M.E., R.J. Stout, C.E. Cushing, P.P. Harper, F.R. Hauer, W.J. Matthews, P.B. Moyle, B. Statzner, and I.R. Wais De Badgen. 1988. Biotic and abiotic controls in river and stream communities. *Journal of the North American Benthological Society* 7:456-479.

Rahel, F. 2002. Homogenization of freshwater faunas. Rev. Ecol. And Systematics 33:291-315.

Reed–Andersen, T., E. Bennett, B. Jorgenson, G. Lauster, D. Lewis, D. Nowacek, J. Rieva, B. Sanderson, and R. Stedman. 2000a. Distribution of recreational boating across lakes: Do landscape variables affect recreational use? Freshwater Biology.

Reed-Andersen, T., S. Carpenter, D. Padilla, and R. Lathrop. 2000b. Predicted impact of zebra mussel (Dreissena polymorpha) invasion on water clarity in Lake Mendota. Can. J. Fish. Aquat. Sci. 57:1617-1626.

Reice, S.R. 1985. Experimental disturbance and the maintenance of species diversity in a stream community. *Oecologia* 67:90-97.

Resh, V.H., A.V. Brown, A.P. Covich, M.E. Gurtz, H.W. Li, G.W. Minshall, S.R. Reice, A.L. Sheldon, J.B. Wallace, and R.C. Wissmar. 1988. The role of disturbance in stream ecology. *Journal of the North American Benthological Society* 7:433-455.

Reynolds, H.L., A. Packer, J.D. Bever, and K. Clay. 2003. Grassroots ecology: Plant-microbe-soil interactions as drivers of plant community structure and dynamics. *Ecology* 84:2281-2291.

Richter, B.D., J.V. Baumgartner, J. Powell and D.P. Braun. 1996. A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* 10: 1163-1174.

Richman S. and S. Dodson. 1983. The effect of food quality on feeding and respiration by Daphnia and Diaptomous. Limnol. and Oceanog. 28:948-956.

Robinson, T.W. 1958. Phreatophytes. Geological Survey Water-Supply Paper 1423. 84 p.

Rood, S. B. and J. M. Mahoney. 1990. Collapse of riparian poplar forests downstream from dams in western prairies: probable causes and prospects for mitigation. *Environmental Management.* 14:451-464.

Rood, S.B., J.B. Mahoney, D.E. Reid, and L. Zilm. 1995. Instream flows and the decline of riparian cottonwoods along the St. Mary River, Alberta. *Canadian Journal of Botany* 73:1250-1260.

Rood, S.B., S. Patino, K. Coombs, and M.T. Tyree. 2000. Branch sacrifice: cavitation-associated drought adaptation of riparian cottonwoods. *Trees* 14:248-257.

Rosgen, D.L. 1996. *Applied river morphology.* Wildland Hydrology, Pagosa Springs, Colorado.

Rosenberg, D.M., and Resh, V.H. 1993. Introduction to freshwater biomonitoring and benthic macroinvertebrates. Pages 1-9 *in* D.M. Rosenberg and V.H. Resh (eds.), *Freshwater Biomonitoring and Benthic Macroinvertebrates*, Chapman and Hall, New York, New York.

Rothrock, J.A., P.K. Barten, and G.L. Ingman. 1998. Land use and aquatic biointegrity in the Blackfoot River watershed, Montana. *Journal of the American Water Resources Association* 34:565-581.

Sager, P. 2004. Inland reservoirs ecosystem conceptual model: *Conceptual ecosystem models for Long-Term Ecological Monitoring in the Great Reservoirs Network*. Great Reservoirs Network Technical Report GLKN/2004/04: 53-71.

Sager, P. and S. Richman. 1991. Functional interaction of phytoplankton and zooplankton along the trophic gradient in Green Bay, Lake Michigan. Can. J. Fish. Aquat. Sci. 48:116-122.

Sager, P., H. Harris, and P. Robinson. 1996. Remedial measures to restore submersed aquatic vegetation in lower Green Bay. Final Report to Wisconsin Department of Natural Resources.

Sala, O.E., and W.K. Lauenroth. 1982. Small rainfall events: An ecological role in semiarid regions. *Oecologia* 53:301-304.

Sample, L.J., J. Steichen, and J.R. Kelley, Jr. 1998. Water quality impacts from low water fords on military training lands. *Journal of the American Water Resources Association* 34:939-949.

Sappington, J.M. 1998. Recreational disturbance of a desert stream fish community: detecting ecological effects of environmental impact. Master's thesis, Department of Biological Sciences, University of Nevada, Las Vegas.

Schade, J.D., E. Marti, J.R. Welter, S.G. Fisher, and N.B. Grimm. 2002. Sources of nitrogen to the riparian zone of a desert stream: implications for riparian vegetation and nitrogen retention. *Ecosystems* 5:68-79.

Scheuhammer, A. and D. Bond. 1991. Factors affecting the determination of total mercury in biological samples by continuous flow cold vapor atomic absorption spectrophotometry. Biol. Trace Element Research 31:157-169.

Schindler, D. 1999. From acid rain to toxic snow. Ambio 28:350-355.

Schindler, D.E., S. Geib, and M. Williams. 2000. Patterns of fish growth along a residential development gradient in north temperate lakes. Ecosystems 3:229-237.

Schultz, T. T., and W. C. Leininger. 1990. Differences in riparian vegetation structure between grazed areas and exclosures. *Journal of Range Management* 43:295-299.

Schulz, R., and M. Liess. 2001a. Acute and chronic effects of particle-associated fenvalerate on stream macroinvertebrates: a runoff simulation study using outdoor microcosms. *Archives of Environmental Contamination and Toxicology* 40:481-488.

Schulz, R., and M. Liess. 2001b. Toxicity of aqueous-phase and suspended particle-associated fenvalerate: chronic effects following pulse-dosed exposure of Limnephilus lunatus (Trichoptera). *Environmental Toxicology and Chemistry* 20:185-191.

Schumm, S.A. 1981. Evolution and response of the fluvial system, sedimentological implications. *The Society of Economic Palentologists and Mineralogists* 31:19-29.

Schumm, S.A. and H.A. Kahn. 1972. Experimental study of channel patterns. *Geological Society of America Bulletin* 83:1755-1770.

Schumm, S.A., and R.W. Lichty. 1963. Channel widening and floodplain construction along Cimarron River in southwestern Kansas. U.S. Geological Survey Professional Paper 352-D.

Schumm, S.A., and R.W. Lichty. 1965. Time, space, and causality in geomorphology. *American Journal of Science* 263:110-119.

Scott, M.L. and J.H. Haskins. 1987. The effects of grazing by Chrysomelid beetles on two wetland herbaceous species. *Bulletin of the Torrey Botanical Club*. **114**: 13-17.

Scott, M.L., G.T. Auble, and J.M. Friedman. 1997. Flood dependency of cottonwood establishment along the Missouri River, Montana, USA. *Ecological Applications* 7:677-690.

Scott M. L., J. M. Friedman and G. T. Auble. 1996. Fluvial Process and the Establishment of Bottomland Trees. Geomorphology 14:327-339.

Scott, M.L., P.B. Shafroth and G.T. Auble. 1999. Response of riparian cottonwoods to alluvial water table declines. *Environmental Management* 23:347-358.

Scott, M.L., G.C. Lines, and G.T. Auble. 2000. Channel incision and patterns of cottonwood stress and mortality along the Mojave River, California. *Journal of Arid Environments* 44:399-414.

Scott, M.L., S.K. Skagen, and M.F. Merligiano. 2003. Relating breeding bird diversity to geomorphic change and grazing in riparian forests. *Conservation Biology* **17**:284-296.

Scott, M.C., E. Reynolds, A. Brasher, A. Caires, and M.E. Miller. June, 2005. The Structure and functioning of riparian and aquatic ecosystems of the Colorado Plateau – Conceptual models to inform monitoring. U.S. Geological Survey – U.S. National Park Service Interagency Report (Draft), 91 p.

Scrimgeour, G.J., and S. Kendall. 2003. Effects of livestock grazing on benthic invertebrates from a native grassland ecosystem. *Freshwater Biology* 48:347-362.

Scrimgeour, G., W. Tonn, C. Paszkowski, and C. Cameron. 2001. Benthic macroinvertebrate biomass and wildfires: Evidence for enrichment of boreal subarctic lakes. Freshwater Biology 46:367-378.

Seastedt, T.R. 2001. Soils. Pages 157-173 *in* W.D. Bowman and T.R. Seastedt (eds.), *Structure and function of an alpine ecosystem: Niwot Ridge, Colorado.* Oxford University Press, New York, New York.

Segelquist, C.A., M.L. Scott, and G.T. Auble. 1993. Establishment of Populus deltoides under simulated alluvial groundwater declines. *American Midland Naturalist* 130:274-285.

Shafroth, P.B., G.T. Auble, and M.L. Scott. 1995. Germination and first-year establishment of a native riparian tree and an invasive exotic. *Conservation Biology*. 9:1169-1175.

Shafroth, P.B., J.C. Stromberg and D.T. Patten. 2000. Woody riparian vegetation response to different alluvial water table regimes. *Western North American Naturalist* 60:66-76.

Shannon, J.P., D.W. Blinn, P.L. Benenati, and K.P. Wilson. 1996. Organic drift in a regulated desert river. *Canadian Journal of Fisheries and Aquatic Sciences* 53:1360-1369.

Shannon, J.P., D.W. Blinn, and L.E. Stevens. 1994. Trophic interactions and benthic animal community structure in the Colorado River, Arizona, U.S.A. *Freshwater Biology* 31:213-220.

Sibley, P.K., K.N. Kaushik, and D.P. Kreutzweiser. 1991. Impact of a pulse application of permethrin on the macroinvertebrate community of a headwater stream. *Environmental Pollution* 70:35-55.

Skjelkvale, B., J. Stoddard, and T. Anderson. 2001. Trends in surface water acidification in Europe and North America (1989-1998). Water, Air and Soil Pollution 130:787-792.

Skujins, J. 1984. Microbial ecology of desert soils. *Advances in Microbial Ecology* 7:49-91.

Smith, M., P. Keevin, P. Mettler-McClure, and R. Barkau. 1998. Effect of the flood of 1993 on Boltonia ducurrens, a rare floodplain plant. *Regulated Rivers-Research and Management.*

Smith, S.D., B.A. Wellington, J.L. Nachlinger, and C.A. Fox. 1991. Functional responses of riparian vegetation to streamflow diversion in the eastern Sierra Nevada. *Ecological Applications* 1:89-97.

Smith, S.E., and D.J. Read. 1997. Mycorrhizal symbiosis. Second edition. Academic Press, San Diego, California. 604 p.

Smith, T., H. H. Shugart, and F.I. Woodward (eds.). 1997. *Plant functional types*. Cambridge University Press, Cambridge. 369 p.

Snyder, K.A., and D.G. Williams. 2000. Water sources used by riparian trees varies among stream types on the San Pedro River, Arizona. *Agricultural and Forest Meteorology* 105:227-240.

Stanford, J.A., Ward J.V., Liss W.J., Frissell C.A., Williams R.N., Lichatowich J.A., and Coutant, C.C. 1996. A general protocol for restoration of regulated rivers. *Regulated Rivers: Research and Management* 12:391-413.

Steinman, A.D. 1996. Effects of grazers on freshwater benthic algae. Pages 341-373 *in* R.J. Stevenson, M.L. Bothwell, and R.L. Lowe (eds.), *Algal ecology: freshwater benthic ecosystems*. Academic Press, San Diego, California.

Stevens, L.E., B.T. Brown, J.M. Simpson, and R.R. Johnson. 1977. The importance of riparian habitat to migrating birds. Pages 156-164 *in* R.R. Johnson and D.A. Jones (tech. coord.), Importance, preservation, and management of riparian habitat: a symposium. U.S. Forest Service General Technical Report RM-43.

Stevens, L.E., J.P. Shannon, and D.W. Blinn. 1997. Colorado River benthic ecology in Grand Canyon, Arizona, USA: Dam, tributary and geomorphological influences. *Regulated Rivers: Research & Management* 13:129-149.

Stoddard, J., C. Driscoll, J. Kahl, and J. Kellogg. 1998. A regional analysis of lake acidification trends for the northeastern U.S., 1982-1994. Env. Monitoring and Assessment. 51:399-413.

Stromberg, J.C. 1993. Riparian mesquite forests: a review of their ecology, threats, and recovery potential. *Journal of the Arizona-Nevada Academy of Sciences* 27:111-124.

Stromberg, J.C., J. Fry, and D.T. Patten. 1997. Marsh development after large floods in an alluvial, arid-land river. *Wetlands* 17:292-300.

Stromberg, J.C., and D.T. Patten. 1991. Instream flow requirements for cottonwoods at Bishop Creek, Inyo County, California. *Rivers* 2:1-11.

Stromberg, J.C., R. Tiller, and B. Richter. 1996. Effects of groundwater decline on riparian vegetation of semiarid regions: the San Pedro, Arizona. *Ecological Applications* 6:113-131.

Szaro, R. C., and C. P. Pase. 1983. Short-term changes in a cottonwood-ash-willow association on a grazed and an ungrazed portion of Little Ash Creek in central Arizona. *Journal of Range Management* 36:382-384.
Taylor, D. M. 1986. Effects of cattle grazing on passerine birds nesting in riparian habitat. *Journal of Range Management* 39:254-258.
Thiere, G., and R. Schulz. 2004. Runoff-related agricultural impact in relation to macroinvertebrate communities of the Lourens River, South Africa. *Water Research* 38:3092-3102.
Tiedemann, A.R., C.E. Conrad, J.H. Dieterich, J.W. Hornbeck, W.F. Megahan, L.A. Viereck, and D.D. Wade. 1979. Effects of fire on water: a state-of-knowledge review. USDA General Technical Report WO-10.
Tilman, D., J. Knops, D. Wedin, P. Reich, M. Ritchie, and E. Siemann. 1997. The influence of functional diversity and composition on ecosystem processes. *Science* 277:1300-1302.
Townsend, C.R., C.J. Arbuckle, T.A. Crowl, and M.R. Scarsbrook. 1997. The relationship between land use and physicochemistry, food resources and macroinvertebrate communities in tributaries of the Taieri River, New Zealand: a hierarchically scaled approach. *Freshwater Biology* 37:177-191.
Trappe, J.M. 1981. Mycorrhizae and productivity of arid and semiarid rangelands. Pages 581-589 *in* J.T. Manassah and E.J. Briskey (eds.), *Advances in food-producing systems for arid and semiarid lands.* Academic Press, New York, New York.
Trimble, S.W., and A.C. Mendel. 1995. The cow as a geomorphic agent- A critical review. *Geomorphology* 13:233-253.
Trombulak, S.C., and C.A. Frissell. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology* 14:18-30.
Tyree, M.T., K.J. Kolb, S.B. Rood, and S. Patiño. 1994. Vulnerability to drought-induced cavitation of riparian cottonwoods in Alberta: a possible factor in the decline of the ecosystem? *Tree Physiology* 14:455-466.
Vahter, M., M. Berglund, and A. Akesson. 2002. Metals and women's health. Env, Research 88:145-155.
Vannote, R.I., G.W. Minshall, K.W. Cummings, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37:120-137.
Vanoni, V.A. (ed.). 1975. Sedimentation Engineering. American Society of Civil Engineers, New York. 620-625
Veenhuis, J.E. 2002. Effects of wildfire on the hydrology of Capulin and Rito de los Frijoles Canyons, Bandelier National Monument, New Mexico. U.S. Geological Survey Water-Resources Investigations Report 02-4152. 39 p.
Vinson, M.R. 2001. Long-term dynamics of an invertebrate assemblage downstream from a large dam. *Ecological Applications* 11:711-730.
Vitousek, P.M. 1994. Factors controlling ecosystem structure and function. Pages 87-97 *in* R.G. Amundson, J.W. Harden, and M.J. Singer (eds.), *Factors of soil formation: a fiftieth anniversary retrospective.* SSSA special publication no. 33. Soil Science Society of America, Madison, Wisconsin.
Waite, I.R., and K.D. Carpenter. 2000. Associations among fish assemblage structure and environmental variables in Willamette Basin Streams, Oregon. *Transactions of the American Fisheries Society* 129:754-770.
Walker, B.H. 1997. Functional types in non-equilibrium systems. Pages 91-103 *in* T.M. Smith, H.H. Shugart, and F.I. Woodward (eds.), *Plant functional types: their relevance to ecosystem properties and global change.* Cambridge University Press, Cambridge.
Walker, B., A. Kinzig, and J. Langridge. 1999. Plant attribute diversity, reslience, and ecosystem function: The nature and significance of dominant and minor species. *Ecosystems* 2:95-113.
Walker, L.R., and F.S. Chapin, III. 1987. Interactions among processes controlling successional change. *Oikos* 50:131-135.

Ward, J.V., and J.A. Stanford. 1983. The serial discontinuity concept of running waters. Pages 29-42 *in* T.D. Fontaine and S.M. Bartell (eds.), *Dynamics of lotic ecosystems,* Ann Arbor Science, Ann Arbor, Michigan.
Wardle, D.A. 2002. *Communities and ecosystems: Linking the aboveground and belowground components.* Princeton University Press, Princeton, New Jersey. 392 p.
WASAL. 2003. Waters of Wisconsin. The Future of Our Aquatic Ecosystems and Resources. Madison, WI. Wisconsin Academy of Science, Arts and Letters.
Watras, C., K. Morrison, R. Hudson, T. Frost, and T. Kratz. 2000. Decreasing mercury in northern Wisconsin: temporal patterns in bulk precipitation and precipitation-dominated lakes. Env. Sci and Tech. 34:4051-4057.
Wedel, W. R. 1986. Central Plains prehistory: Holocene environments and culture change in the Republican River basin. University of Nebraska Press, Lincoln.
Weigel, B.M., J. Lyons, L.K. Paine, S.I. Dodson, and D.J. Undersander. 2000. Using stream macroinvertebrates to compare riparian land use practices on cattle farms in Southwestern Wisconsin. *Journal of Freshwater Ecology* 15:93-106.
Weisberg, S.B., A.J. Janicki, J. Gerritesen, and H.T. Wilson. 1990. Enhancement of benthic macroinvertebrates by minimum flow from a hydroelectric dam. *Regulated Rivers: Research & Management* 5:265-277.
Wetzel, R. G. 1983. Limnology, Second Edition. Saunders, Philadelphia. 767 pp.
Wetzel, R.G. 1979. The role of the littoral zone and detritus on lake metabolism. Arch. Hydrobiol. Beih. 13:145-161.
Whisenant, S.G. 1999. *Repairing damaged wildlands: A process-oriented, landscape-scale approach.* Cambridge University Press, Cambridge. 312 p.
Whitford, W.G. 1996. The importance of the biodiversity of soil biota in arid ecosystems. *Biodiversity and Conservation* 5:185-195.
Whitford, W.G. 2002. *Ecology of desert systems.* Academic Press, San Diego, California. 343 p.
Winter, T.C. 1999. Relations of streams, reservoirs, and wetlands to groundwater flow systems. *Hydrogeology Journal* 7:28-45.
Woessner, W.W. 2000. Stream and fluvial plain ground water interactions: rescaling hydrogeological thought. *Ground Water* 38:423-429.
Wood, P.J., and G.E. Petts. 1994. Low flows and recovery of macroinvertebrates in a small regulated chalk stream. *Regulated Rivers: Research & Management* 9:303-316.
Woodford, J. and M. Meyer. 2003. Impacts of lakeshore development on green frog abundance. Biological Conservation 110:73-78.
Woodward, D.F., W.G. Brumbaugh, A.J. DeLonay, E.E. Little, and C.E. Smith. 1994. Effects on rainbow trout fry of a metals-contaminated diet of benthic invertebrates from the Clark Fork River, Montana. *Transactions of the American Fisheries Society* 123:51-62.
Wynn, K.H., N.J. Bauch, and N.E. Driver. 2001. Gore Creek Watershed, Colorado-Assessment of historical and current water quantity, water quality, and aquatic ecology, 1968-98. U.S. Geological Survey Water-Resources Investigations Report 99-4270.
Zimmer, R.R., and T.E. Lisle. 1998. Hydrology. Pages 43-68, *in* R.J. Naiman and R.E. Bilby (eds.), River Ecology and Management, Springer-Verlag, New York, New York, USA.
Zimmerman, R.C. 1969. Plant ecology of an arid basin, Tres Alamos-Reding area, southeastern Arizona. United States Geological Survey Professional Paper 485-D.

CITED IN TEXT BUT NO REFERECNCE YET
Anderson and Cooper 2000
Archer and Smeins 1991
Auble et al. 1997
Backer et al. 1986
Bardsett and Wardle 2003
Behmer and Hawkins 1986
Bethlenfalvay and Dakessian 1984

Bradley and Smith 1986
Briske 1991
Briske and Richards 1995
Brode and Bury 1984
Busch et al. 1995
Cooke and Reeves 1972
Davis et al. 2000
Dunne 1978
Falck et al. 2003
Fleishman et al. 1999
Haden et al. 2003
Harig and Bain 1998
Knutson et al 1996
Lugo et al. 1990
Magnuson et al 2000
Magnuson in press
Matthews 1988
Naiman et al. 1993
Naiman and Rogers 1997
Pollock et al. 1998
Richter and Richter 2000
Stromberg et al. 1991
Thorp and Covich 1991
Thurow 1991
Vieira 2004
Vieira et al. 2004
Wallace and O'Hop 1985
Welcomme 1985